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LARGE-AREA PROTON BEAMS ESTABLISHED AT THE NASA SPACE RADIATION EFFECTS LABORATORY IN THE ENERGY RANGE FROM 31 TO 225 MeV

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16. Abstract

In a series of experiments to produce large-area proton beams at the NASA Space Radiation Effects Laboratory a total of 14 beam configurations were established. The proton beams varied in size from 11.3 cm horizontal by 9.7 cm vertical for full width at half maximum to 78 cm horizontal by 78.5 cm vertical for full width at half maximum and covered an energy range from 31 MeV to 225 MeV. Horizontal and vertical profiles of each beam configuration were determined by using a foil activation technique. Each profile was fitted by the method of least squares to a Gaussian function, with the full width at half maximum value indicated. Repeatability of beam shape and proton flux has been shown to be very good.

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SUMMARY

In a series of experiments to produce large-area proton beams at the NASA Space Radiation Effects Laboratory a total of 14 beam configurations were established. The proton beams varied in size from 11.3 cm horizontal by 9.7 cm vertical for full width at half maximum to 78 cm horizontal by 78.5 cm vertical for full width at half maximum and covered an energy range from 31 MeV to 225 MeV. Horizontal and vertical profiles of each beam configuration were determined by using a foil activation technique. Each profile was fitted by the method of least squares to a Gaussian function, with the full width at half maximum value indicated. Repeatability of beam shape and proton flux has been shown to be very good.

INTRODUCTION

The National Aeronautics and Space Administration has a Space Radiation Effects Laboratory (fig. 1), operated under contract by the College of William and Mary, which is suitably designed for studies of radiation effects on both biological and physical targets. A 600-MeV proton synchrocyclotron (figs. 2 and 3), the facility's major machine, provides both small- and large-area beams over a wide energy range. Beams can be obtained in both the combined target area and the proton target area. This report covers only the large-area proton beams in the combined target area.

The synchrocyclotron has two interchangeable proton extraction systems, one at approximately 600 MeV and one at approximately 300 MeV. The primary extracted beams are degraded to lower energies by the use of remotely controlled copper absorbers located in beam degraders 1 and 2 of the proton beam transport system (figs. 4 and 5). The final beam configuration at the target position in the combined target area is dependent upon how well 21 magnets located in the proton beam transport system can be manually optimized from the beam profile standpoint. The characteristics of 14 large-area proton beam configurations, including such parameters as magnet settings, beam energy, relative

intensity profiles, and proton profiles in $\frac{\text{protons/cm}^2}{\text{min}}$, are summarized in this report. Similar characteristics for small area focused beams have been reported in references 1 and 2.

ABBREVIATIONS

BC	beam collimator
BD	beam degrader
BM	beam monitor
BS	beam stop
CTA	combined target area
FWHM	full width at half maximum
M	bending magnet
NASA	National Aeronautics and Space Administration
PBTS	proton beam transport system
PTA	proton target area
Q	quadrupole magnet
SREL	Space Radiation Effects Laboratory

EXPERIMENTAL PROCEDURES

Methods Used To Obtain Large-Area Beams

Two methods were used to obtain large-area beams at the target position. The preferred technique, because of the lower background radiation, employed quadrupole magnet defocusing and was used for nine of the beams. Five large-area beams were obtained by Coulomb scattering of the proton beam through copper absorbers located on the exit window of BM4 (fig. 5). Other large-area beams were obtained by degrading with copper

absorbers located in BD1 and then Coulomb scattering the beam on the BM4 exit window. Both Coulomb scattering methods were used to obtain beam intensities higher than those obtained by magnet defocusing and to improve intensity homogeneity.

Lower energy, large-area beams were obtained by degrading the primary extracted beam (325 MeV) through copper absorbers in BD1 and then quadrupole-magnet defocusing with Q13 and Q14 (fig. 5). Magnet and degrader settings were determined for each large-area beam configuration and are given in tables 1 to 10. The energy of all beams was determined by using a range-energy spectrometer.

Monitoring Techniques

Foil activation is considered one of the best techniques for determining high-energy proton beam intensities. The $C^{12}(p,pn)C^{11}$ reaction is widely used for beam monitoring since the cross section is known to within ±5 percent over a proton energy range from 50 MeV to the GeV region (ref. 3). The induced C^{11} atoms decay to B^{11} by positron emission with a half-life of 20.5 min and a maximum energy of 0.97 MeV.

Polystyrene samples with a 2.54-cm diameter and a 0.32-cm thickness were placed in the beam area to monitor the vertical and horizontal profiles of the beam as illustrated in figure 6. For the determination of absolute C^{11} activity induced in the polystyrene samples, a gamma counting system was chosen for this experiment. The emitted positrons were stopped in a 1-mm-thick aluminum capsule surrounding the polystyrene disk. Gamma rays produced by positron annihilation were then counted with a NaI(Tl) crystal for a live time of 1 min on a pulse height analyzer. Each array of polystyrene disks was irradiated for a time equal to 3 half-lives (61.5 min). Proton beam intensity was monitored throughout the irradiation time with a secondary emission chamber to assure beam flux invariance.

Horizontal and vertical profiles were determined at both 3.05 m and 7.62 m from the exit window of BM4 in the CTA.

Calibration of Detector System

Several precision gamma standard sources with accuracies within ±2 percent were used for calibration of the 7.62 cm by 7.62 cm NaI(Tl) crystal detector system. Nominal source-to-detector distances of 0, 5, and 10 cm were chosen depending on the source strength of each irradiated polystyrene disk.

Crystal efficiency was determined for each source-to-detector distance. Since the samples used were not point sources, corrections were made in the calibrated efficiencies and were found to be 1.5 percent for the 2.54-cm-diameter samples.

Proton Flux Determination

From the calibrations just described, it was possible to determine the number of gamma rays being emitted from a source of unknown strength at a distance of 0, 5, or 10 cm. Since the cross sections for the $C^{12}(p,pn)C^{11}$ reaction are known in addition to the calibration results, it was possible to calculate the number of protons incident on each target.

The total activity A_T from an irradiated disk is given by

$$A_T = N_O \sigma \Phi(t)\left(1 - e^{-\lambda t}\right)$$

where

N_o	number of C^{12} atoms/cm^2
σ	cross section for $C^{12}(p,pn)C^{11}$ reaction, cm^2
$\Phi(t)$	protons/sec intercepted on disk
t	duration of irradiation, min
λ	decay constant, $\frac{0.693}{T_{\frac{1}{2}}} = 0.0338 \text{ min}^{-1}$
$T_{\frac{1}{2}}$	half-life, min

By integrating the peak associated with the 0.511-MeV gamma rays and using the calibration data, A_T can easily be determined for each disk. The only unknown quantity is therefore $\Phi(t)$ which is calculated from the other parameters. After $\Phi(t)$ is determined, it is then possible to determine the flux.

RESULTS AND DISCUSSION

Large-Area Beams Obtained by Magnet Defocusing

Nine of the large-area beams were obtained by degrading the 325-MeV primary extracted beam to the desired energy in BD1 and then blowing up the degraded beam by defocusing the last pair of quadrupole magnets (Q13 and Q14) in the PBTS. The defocused beam does not impinge on the radial structure of BM4. This technique is used to minimize unwanted secondary particles at the target position in the CTA. It can be seen from

figure 5 that the lower energy degraded beams are bent through an angle of 45° before entering the target area or being absorbed by the walls. Therefore, most of the secondary particles produced in BD1 are lost from the degraded beam as it turns and do not contribute to the flux. Beam intensities available at the various energies are shown in figure 7.

Horizontal and vertical profiles of these nine large-area proton beams are presented in figures 8 to 16. These profiles were obtained 3.05 m and 7.62 m from BM4 exit window in the CTA. The curves are given for each energy in terms of $\frac{\text{protons/cm}^2}{\text{min}}$ as a function of detector distance from the center of the beam pipe (cm). Full width at half maximum values are given in cm for each profile. In figure 6 with the beam into the paper, the labels LEFT and TOP indicate, respectively, the horizontal and vertical profiles determined to the left of zero. Data points are represented as solid dots and the horizontal bars represent the detector diameter of 2.54 cm. The vertical error bars represent a ±8-percent spread in beam flux. (See appendix.) Each profile was fitted by the method of least squares to a Gaussian function which is indicated by the curve.

The maximum proton flux available at 3.05 m from BM4 exit window for the large-area beams was found to be $9.15 \times 10^9 \frac{\text{protons/cm}^2}{\text{min}}$ for the 225-MeV beam (fig. 8). This beam has a horizontal profile FWHM of 11.3 cm and a vertical profile FWHM of 9.7 cm. The proton flux drops to $2.55 \times 10^9 \frac{\text{protons/cm}^2}{\text{min}}$ at 7.62 m from BM4 exit window at this energy (fig. 9). However, the FWHM for both horizontal and vertical profiles increases to 18.2 cm at 7.62 m. A very low flux of approximately $3.53 \times 10^7 \frac{\text{protons/cm}^2}{\text{min}}$ was found for the 50-MeV beam at 3.05 m from BM4 exit window (fig. 16); therefore, profiles were not determined at 7.62 m. The beam with the largest area recorded is the 95-MeV beam at 7.62 m with a horizontal FWHM of 53 cm and a vertical FWHM of 45 cm (fig. 13).

The magnet degrader settings required to obtain the different beam characteristics are given in tables 1 to 10; the values of FWHM and proton flux are given in table 11.

Large-Area Beams Obtained by Coulomb Scattering

This portion of the experiment was conducted to get a sampling of beams that could be obtained by two different methods and provide future experimenters with information required to establish beams for their specific use. All large-area proton beams for energies of 194, 146, 142, 90, and 31 MeV were obtained by Coulomb scattering. Horizontal and vertical profiles were made at 3.05 m from BM4 exit window and are shown in figures 17 to 21. In one method used to obtain a large-area beam, the 325-MeV proton beam was transported to the CTA where it was then degraded and scattered by copper placed on BM4 exit window. This method was used to determine the available flux in the CTA.

Profiles of the 146-MeV beam obtained by this method are shown in figure 18. A proton flux of $1.76 \times 10^9 \frac{\text{protons/cm}^2}{\text{min}}$ was measured on the horizontal profile and a flux of $1.8 \times 10^9 \frac{\text{protons/cm}^2}{\text{min}}$ was measured on the vertical profile. This beam was also found to have a horizontal FWHM of 54 centimeters and a vertical FWHM of 51 centimeters.

Figure 19 shows the profiles of a nominal 146-MeV (actually 142 MeV) beam repeated by degrading the 325-MeV beam to 225 MeV in the magnet hall by using BD1 and then degrading the 225-MeV beam to 142 MeV by using copper absorbers located on BM4 exit window. The 142-MeV beam gave the highest proton flux $\left(3.0 \times 10^9 \frac{\text{protons/cm}^2}{\text{min}}\right)$ of any of the Coulomb scattered beams. Secondary neutrons produced by this method were negligible. (See appendix.)

In general, large-area beams obtained by the Coulomb scattering method were found to be larger, more uniform, and of higher intensity than those obtained by magnet defocusing, but their use will depend on the requirements of any particular experiment and on tolerance requirements of neutrons and prompt gamma rays.

Repeatability

Since many parameters are associated with each given beam condition, it was necessary to determine the degree to which the overall conditions could be repeated. Profiles were first determined for several large-area beams and later repeated for comparison. A time period of several days between runs was sufficient for repeatability studies. Photographs of the beam were also taken. The entire system was found to be repeatable (within experimental accuracy) in terms of beam area and proton flux for a period of up to 6 months.

CONCLUDING REMARKS

Several large-area beams in the energy range from 31 MeV to 225 MeV have been set up at the NASA Space Radiation Effects Laboratory. Beams are available over a wide energy spectrum to meet the requirements of radiation effects work including radiation biology experiments. Although the energy range of the present study was from 31 MeV to 225 MeV, large-area beams up to 600 MeV can be obtained. The measured beams have proved to be very stable, uniform, and repeatable.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 15, 1969.

APPENDIX

ERRORS IN FOIL ACTIVATION TECHNIQUE FOR PROTON BEAM MONITORING

The largest error involved in the foil activation technique for proton beam monitoring is in the uncertainty of the value of cross section for the $C^{12}(p,pn)C^{11}$ reaction. This error is reported to be approximately ±5 percent over the energy range considered (ref. 3).

Several investigators (refs. 4 and 5) have reported a loss of activity in this technique due to the diffusion process of C^{11} atoms in a gaseous form. As much as a 15-percent loss has been indicated for very thin samples. However, the loss of activity for the thicker samples used in this experiment was observed to be less than ±0.5 percent. This loss of activity was experimentally determined by irradiating a stack of three identical polystyrene targets for a time equal to 3 half-lives corresponding to the $C^{12}(p,pn)C^{11}$ reaction. Each target was then counted and relative activities were determined. All targets were found to have the same activity to within ±0.5 percent.

All the standard gamma sources used were calibrated to an accuracy of ±2 percent or better by the International Atomic Energy Agency, Vienna, Austria.

Integration of the peak associated with the 0.511-MeV gamma rays was necessary to determine the total number of emitted gamma rays. This integration was accomplished by using a computer to subtract out background counts and to determine the limits of integration. The error in the total integration was then found since the error was known for the number of counts in each channel. A ±3-percent error was found for evaluation of the peak area.

The proton beam intensity fluctuation during an irradiation was determined by continuous monitoring of the current from a secondary emission chamber. Current readings were recorded at 1-min intervals and fluctuated ±2 percent during the entire irradiation.

Contributions of the $C^{12}(n,2n)C^{11}$ reaction and other reactions to the total sample activity were found to be negligible for the energies considered. This fact was verified by counting several targets for 10 half-lives and noting the linearity of the data.

The attenuation of gamma rays in the polystyrene target and aluminum capsule also contributed an error. This attenuation can be calculated quite easily if all gamma rays are assumed to be created at the geometrical center of the polystyrene target. The intensity of gamma rays reaching the NaI(Tl) crystal is given by

$$I = I_o e^{-\left(\mu_p d_p + \mu_{Al} d_{Al} + \mu_a d_a\right)}$$

where

I_o	total intensity of gamma rays produced at origin
μ_p	attenuation coefficient of polystyrene, 0.086 cm^{-1}
μ_{Al}	attenuation coefficient of aluminum, 0.23 cm^{-1}
μ_a	attenuation coefficient of air, 0.111×10^{-3} cm^{-1}
d_p	thickness of polystyrene, 0.159 cm
d_{Al}	thickness of aluminum, 0.100 cm
d_a	thickness of air, 10.000 cm

Substituting the appropriate values in the intensity expression gives the gamma intensity at the face of the NaI(Tl) crystal as

$$I = 0.963 I_o$$

A total of 3.7 percent of the gamma rays were attenuated.

Other errors, such as inaccuracy in the calculated number of C^{12} atoms/cm^2 and time measurements, were estimated to be ±2 percent.

Therefore, the overall root-mean-square error was calculated to be ±7.8 percent.

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TABLE 1.- MAGNET POWER SUPPLY SETTINGS FOR A LARGE-AREA 225-MeV PROTON BEAM IN THE COMBINED TARGET AREA AT SREL

Extraction platter used		300 MeV
Copper degrader thickness (BD1)	4.45 cm	(39.65 gm/cm^2)
Degraded energy		225 MeV
Distance from BM4 exit window of profile measurement	3.05 m	7.62 m
Beam dimensions (full width at half maximum) for –		
Horizontal profile	11.3 cm	18.2 cm
Vertical profile	9.7 cm	18.2 cm
Main magnet reading		67.40 mV
Diverted current		+80.0 A

Power supply and shunt numbers	Magnet	Digital voltmeter reading, mV
PS 1	M2/M3	31.77
PS 2	M4	27.07
PS 3	M5	27.07
PS 4	Q1A/Q2A	16.16
PS 5	Q5	30.20
PS 6	Q8	20.99
PS 7	Q2/Q3	19.60
PS 8	Q6/Q10	31.67
PS 9	--------	-----
PS 10	Q1	22.78
PS 11	Q7	27.07
PS 12	Q9	22.82
PS 13	--------	-----
PS 14	--------	-----
PS 15	Q4	22.00
PS 16	Q11	27.85
PS 17	Q12	22.93
PS 18	Q13	23.00
PS 19	Q14	10.00
PS 20	M1	8.05
Shunt 1	M2/M3	-----
Shunt 2	Q1A/Q2A	-----
Shunt 3	Q2/Q3	+11.82
Shunt 4	Q6/Q10	-5.24
Shunt 5	--------	-----

TABLE 2.- MAGNET POWER SUPPLY SETTINGS FOR A LARGE-AREA 155-MeV PROTON BEAM IN THE COMBINED TARGET AREA AT SREL

Extraction platter used		300 MeV
Copper degrader thickness (BD1)		6.98 cm ($62.31\ gm/cm^2$)
Degraded energy		155 MeV
Distance from BM4 exit window of profile measurement	3.05 m	7.62 m
Beam dimensions (full width at half maximum) for –		
Horizontal profile	17.2 cm	32.8 cm
Vertical profile	26.6 cm	47.2 cm
Main magnet reading		67.88 mV
Diverted current		+78.00 A

Power supply and shunt numbers	Magnet	Digital voltmeter reading, mV
PS 1	M2/M3	31.73
PS 2	M4	21.97
PS 3	M5	22.73
PS 4	Q1A/Q2A	16.10
PS 5	Q5	27.10
PS 6	Q8	30.50
PS 7	Q2/Q3	20.20
PS 8	Q6/Q10	32.75
PS 9	--------	-----
PS 10	Q1	22.85
PS 11	Q7	29.74
PS 12	Q9	17.76
PS 13	--------	-----
PS 14	--------	-----
PS 15	Q4	23.08
PS 16	Q11	27.10
PS 17	Q12	31.00
PS 18	Q13	37.50
PS 19	Q14	36.20
PS 20	M1	8.00
Shunt 1	M2/M3	-----
Shunt 2	Q1A/Q2A	-----
Shunt 3	Q2/Q3	+12.10
Shunt 4	Q6/Q10	-4.10
Shunt 5	--------	-----

TABLE 3.- MAGNET POWER SUPPLY SETTINGS FOR A LARGE-AREA 95-MeV PROTON BEAM IN THE COMBINED TARGET AREA AT SREL

Extraction platter used		300 MeV
Copper degrader thickness (BD1)	8.57 cm	(76.47 gm/cm^2)
Degraded energy		95 MeV
Distance from BM4 exit window of profile measurement	3.05 m	7.62 m
Beam dimensions (full width at half maximum) for –		
Horizontal profile	19.0 cm	53.0 cm
Vertical profile	22.6 cm	45.0 cm
Main magnet reading		+67.43 mV
Diverted current		+80.0 A

Power supply and shunt numbers	Magnet	Digital voltmeter reading, mV
PS 1	M2/M3	31.87
PS 2	M4	17.02
PS 3	M5	17.02
PS 4	Q1A/Q2A	15.59
PS 5	Q5	18.06
PS 6	Q8	20.56
PS 7	Q2/Q3	20.76
PS 8	Q6/Q10	24.05
PS 9	--------	-----
PS 10	Q1	24.21
PS 11	Q7	22.65
PS 12	Q9	13.33
PS 13	--------	-----
PS 14	--------	-----
PS 15	Q4	30.02
PS 16	Q11	18.32
PS 17	Q12	16.42
PS 18	Q13	30.00
PS 19	Q14	30.00
PS 20	M1	8.39
Shunt 1	M2/M3	-----
Shunt 2	Q1A/Q2A	-----
Shunt 3	Q2/Q3	+12.48
Shunt 4	Q6/Q10	-14.50
Shunt 5	--------	-----

TABLE 4.- MAGNET POWER SUPPLY SETTINGS FOR A LARGE-AREA 75-MeV PROTON BEAM IN THE COMBINED TARGET AREA AT SREL

Extraction platter used		300 MeV
Copper degrader thickness (BD1)	8.89 cm	(79.30 gm/cm^2)
Degraded energy		75 MeV
Distance from BM4 exit window of profile measurement	3.05 m	7.62 m
Beam dimensions (full width at half maximum) for –		
Horizontal profile	14.0 cm	36.0 cm
Vertical profile	19.2 cm	36.0 cm
Main magnet reading		+67.40 mV
Diverted current		+81.0 A

Power supply and shunt numbers	Magnet	Digital voltmeter reading, mV
PS 1	M2/M3	31.87
PS 2	M4	15.59
PS 3	M5	15.55
PS 4	Q1A/Q2A	15.55
PS 5	Q5	19.53
PS 6	Q8	19.22
PS 7	Q2/Q3	25.75
PS 8	Q6/Q10	21.45
PS 9	--------	-----
PS 10	Q1	24.23
PS 11	Q7	18.63
PS 12	Q9	15.22
PS 13	--------	-----
PS 14	--------	-----
PS 15	Q4	30.00
PS 16	Q11	29.46
PS 17	Q12	28.83
PS 18	Q13	29.93
PS 19	Q14	32.85
PS 20	M1	8.39
Shunt 1	M2/M3	-----
Shunt 2	Q1A/Q2A	-----
Shunt 3	Q2/Q3	+12.5
Shunt 4	Q6/Q10	-3.74
Shunt 5	--------	-----

TABLE 5.- MAGNET POWER SUPPLY SETTINGS FOR A LARGE-AREA 50-MeV PROTON BEAM IN THE COMBINED TARGET AREA AT SREL

Extraction platter used . . . . 300 MeV
Copper degrader thickness (BD1) . . . . 9.53 cm (84.96 gm/cm2)
Degraded energy . . . . 50 MeV
Distance from BM4 exit window of profile measurement . . . . 3.05 m
Beam dimensions (full width at half maximum) for –
  Horizontal profile . . . . 45.0 cm
  Vertical profile . . . . 35.0 cm
Main magnet reading . . . . 67.37 mV
Diverted current . . . . +80.0 A

Power supply and shunt numbers	Magnet	Digital voltmeter reading, mV
PS 1	M2/M3	32.52
PS 2	M4	13.40
PS 3	M5	13.75
PS 4	Q1A/Q2A	13.98
PS 5	Q5	18.03
PS 6	Q8	17.82
PS 7	Q2/Q3	20.24
PS 8	Q6/Q10	20.98
PS 9	--------	-----
PS 10	Q1	24.22
PS 11	Q7	17.92
PS 12	Q9	9.77
PS 13	--------	-----
PS 14	--------	-----
PS 15	Q4	29.76
PS 16	Q11	14.48
PS 17	Q12	14.74
PS 18	Q13	30.01
PS 19	Q14	25.00
PS 20	M1	8.36
Shunt 1	M2/M3	-----
Shunt 2	Q1A/Q2A	-----
Shunt 3	Q2/Q3	+12.17
Shunt 4	Q6/Q10	-12.74
Shunt 5	--------	-----

TABLE 6.- MAGNET POWER SUPPLY SETTINGS FOR A LARGE-AREA 194-MeV PROTON BEAM IN THE COMBINED TARGET AREA AT SREL

Extraction platter used . . . . 300 MeV
Copper degrader thickness (BD1) . . . . 4.44 cm (39.65 gm/cm^2)
Copper degrader thickness (BM4) . . . . 1.15 cm (10.24 gm/cm^2)
Degraded energy . . . . 194 MeV
Distance from BM4 exit window of profile measurement . . . . 3.05 m
Beam dimensions (full width at half maximum) for –
Horizontal profile . . . . 24.0 cm
Vertical profile . . . . 24.0 cm
Main magnet reading . . . . 67.92 mV
Diverted current . . . . +27 A

Power supply and shunt numbers	Magnet	Digital voltmeter reading, mV
PS 1	M2/M3	31.71
PS 2	M4	27.39
PS 3	M5	27.50
PS 4	Q1A/Q2A	16.12
PS 5	Q5	30.20
PS 6	Q8	21.00
PS 7	Q2/Q3	14.60
PS 8	Q6/Q10	31.70
PS 9	--------	----
PS 10	Q1	22.81
PS 11	Q7	27.10
PS 12	Q9	22.80
PS 13	--------	----
PS 14	--------	----
PS 15	Q4	22.00
PS 16	Q11	42.06
PS 17	Q12	30.05
PS 18	Q13	41.12
PS 19	Q14	27.01
PS 20	M1	7.98
Shunt 1	M2/M3	----
Shunt 2	Q1A/Q2A	----
Shunt 3	Q2/Q3	11.82
Shunt 4	Q6/Q10	5.30
Shunt 5	--------	----

TABLE 7.- MAGNET POWER SUPPLY SETTINGS FOR A LARGE-AREA 146-MeV PROTON BEAM IN THE COMBINED TARGET AREA AT SREL

Extraction platter used	300 MeV
Copper degrader thickness (BM4)	7.19 cm (63.97 gm/cm^2)
Degraded energy	146 MeV
Distance from BM4 exit window of profile measurement	3.05 m
Beam dimensions (full width at half maximum) for –	
Horizontal profile	54.0 cm
Vertical profile	51.0 cm
Main magnet reading	67.30 mV
Diverted current	+85.0 A

Power supply and shunt numbers	Magnet	Digital voltmeter reading, mV
PS 1	M2/M3	32.50
PS 2	M4	33.72
PS 3	M5	34.31
PS 4	Q1A/Q2A	19.07
PS 5	Q5	15.24
PS 6	Q8	30.45
PS 7	Q2/Q3	16.01
PS 8	Q6/Q10	25.45
PS 9	--------	----
PS 10	Q1	22.80
PS 11	Q7	41.75
PS 12	Q9	10.21
PS 13	--------	----
PS 14	--------	----
PS 15	Q4	22.48
PS 16	Q11	31.67
PS 17	Q12	38.20
PS 18	Q13	50.04
PS 19	Q14	68.02
PS 20	M1	8.94
Shunt 1	M2/M3	----
Shunt 2	Q1A/Q2A	----
Shunt 3	Q2/Q3	+9.56
Shunt 4	Q6/Q10	-4.45
Shunt 5	--------	----

TABLE 8.- MAGNET POWER SUPPLY SETTINGS FOR A LARGE-AREA 142-MeV PROTON BEAM IN THE COMBINED TARGET AREA AT SREL

Extraction platter used . . . . 300 MeV
Copper degrader thickness (BD1) . . . . 4.44 cm (39.65 gm/cm^2)
Copper degrader thickness (BM4) . . . . 2.84 cm (25.42 gm/cm^2)
Degraded energy . . . . 142 MeV
Distance from BM4 exit window of profile measurement . . . . 3.05 m
Beam dimensions (full width at half maximum) for –
Horizontal profile . . . . 40 cm
Vertical profile . . . . 41 cm
Main magnet reading . . . . 67.92 mV
Diverted current . . . . +27 A

Power supply and shunt numbers	Magnet	Digital voltmeter reading, mV
PS 1	M2/M3	31.71
PS 2	M4	27.39
PS 3	M5	27.50
PS 4	Q1A/Q2A	16.12
PS 5	Q5	30.20
PS 6	Q8	21.00
PS 7	Q2/Q3	19.60
PS 8	Q6/Q10	31.76
PS 9	--------	----
PS 10	Q1	22.81
PS 11	Q7	27.10
PS 12	Q9	22.80
PS 13	--------	----
PS 14	--------	----
PS 15	Q4	22.00
PS 16	Q11	42.06
PS 17	Q12	30.05
PS 18	Q13	41.12
PS 19	Q14	27.01
PS 20	M1	7.98
Shunt 1	M2/M3	----
Shunt 2	Q1A/Q2A	----
Shunt 3	Q2/Q3	11.82
Shunt 4	Q6/Q10	5.30
Shunt 5	--------	----

TABLE 9.- MAGNET POWER SUPPLY SETTINGS FOR A LARGE-AREA 90-MeV PROTON BEAM IN THE COMBINED TARGET AREA AT SREL

Extraction platter used	300 MeV
Copper degrader thickness (BD1)	4.44 cm (39.65 gm/cm^2)
Copper degrader thickness (BM4)	4.17 cm (37.24 gm/cm^2)
Degraded energy	90 MeV
Distance from BM4 exit window of profile measurement	3.05 m
Beam dimensions (full width at half maximum) for –	
Horizontal profile	56 cm
Vertical profile	58 cm
Main magnet reading	67.92 mV
Diverted current	+27 A

Power supply and shunt numbers	Magnet	Digital voltmeter reading, mV
PS 1	M2/M3	31.71
PS 2	M4	27.39
PS 3	M5	27.50
PS 4	Q1A/Q2A	16.12
PS 5	Q5	30.20
PS 6	Q8	21.00
PS 7	Q2/Q3	19.60
PS 8	Q6/Q10	31.76
PS 9	--------	----
PS 10	Q1	22.81
PS 11	Q7	27.10
PS 12	Q9	22.80
PS 13	--------	----
PS 14	--------	----
PS 15	Q4	22.00
PS 16	Q11	42.06
PS 17	Q12	30.05
PS 18	Q13	41.12
PS 19	Q14	27.01
PS 20	M1	7.98
Shunt 1	M2/M3	----
Shunt 2	Q1A/Q2A	----
Shunt 3	Q2/Q3	11.82
Shunt 4	Q6/Q10	5.30
Shunt 5	--------	----

TABLE 10.- MAGNET POWER SUPPLY SETTINGS FOR A LARGE-AREA 31-MeV PROTON BEAM IN THE COMBINED TARGET AREA AT SREL

Extraction platter used	300 MeV
Copper degrader thickness (BD1)	4.44 cm (39.65 gm/cm2)
Copper degrader thickness (BM4)	5.08 cm (45.32 gm/cm2)
Degraded energy	31 MeV
Distance from BM4 exit window of profile measurement	3.05 m
Beam dimensions (full width at half maximum) for –	
Horizontal profile	78 cm
Vertical profile	78.5 cm
Main magnet reading	67.92 mV
Diverted current	+27 A

Power supply and shunt numbers	Magnet	Digital voltmeter reading, mV
PS 1	M2/M3	31.71
PS 2	M4	27.39
PS 3	M5	27.50
PS 4	Q1A/Q2A	16.12
PS 5	Q5	30.20
PS 6	Q8	21.00
PS 7	Q2/Q3	19.60
PS 8	Q6/Q10	31.76
PS 9	--------	----
PS 10	Q1	22.81
PS 11	Q7	27.10
PS 12	Q9	22.80
PS 13	--------	----
PS 14	--------	----
PS 15	Q4	22.00
PS 16	Q11	42.06
PS 17	Q12	30.05
PS 18	Q13	41.12
PS 19	Q14	27.01
PS 20	M1	7.98
Shunt 1	M2/M3	----
Shunt 2	Q1A/Q2A	----
Shunt 3	Q2/Q3	11.82
Shunt 4	Q6/Q10	5.30
Shunt 5	--------	----

TABLE 11.- LARGE-AREA BEAMS AVAILABLE IN COMBINED TARGET AREA AT SREL

Proton energy, MeV	Full width at half maximum, cm, for –				Maximum flux, $\frac{\text{protons/cm}^2}{\text{min}}$, for –			
	Horizontal profile at –		Vertical profile at –		Horizontal profile at –		Vertical profile at –	
	3.05 m	7.62 m	3.05 m	7.62 m	3.05 m	7.62 m	3.05 m	7.62 m
225	11.3	18.2	9.7	18.2	9.15×10^9	2.55×10^9	8.25×10^9	2.55×10^9
155	17.2	32.8	26.6	47.2	1.8×10^9	4.45×10^8	1.35×10^9	3×10^8
95	19.0	53.0	22.6	45.0	4.8×10^8	8.66×10^7	4.4×10^8	8.1×10^7
75	14.0	36.0	19.2	36.0	8.3×10^8	1.9×10^8	8.3×10^8	1.8×10^8
50	45.0	---	35.0	---	3.5×10^7	---------	3.5×10^7	---------
*194	24.0	---	24.0	---	2.0×10^9	---------	2.0×10^9	---------
*146	54.0	---	51.0	---	1.76×10^9	---------	1.80×10^9	---------
*142	40	---	41	---	3×10^9	---------	2.9×10^9	---------
*90	56.0	---	58.0	---	3.57×10^8	---------	3.37×10^8	---------
*31	78.0	---	78.5	---	2.7×10^8	---------	2.65×10^8	---------

*Coulomb scattered.

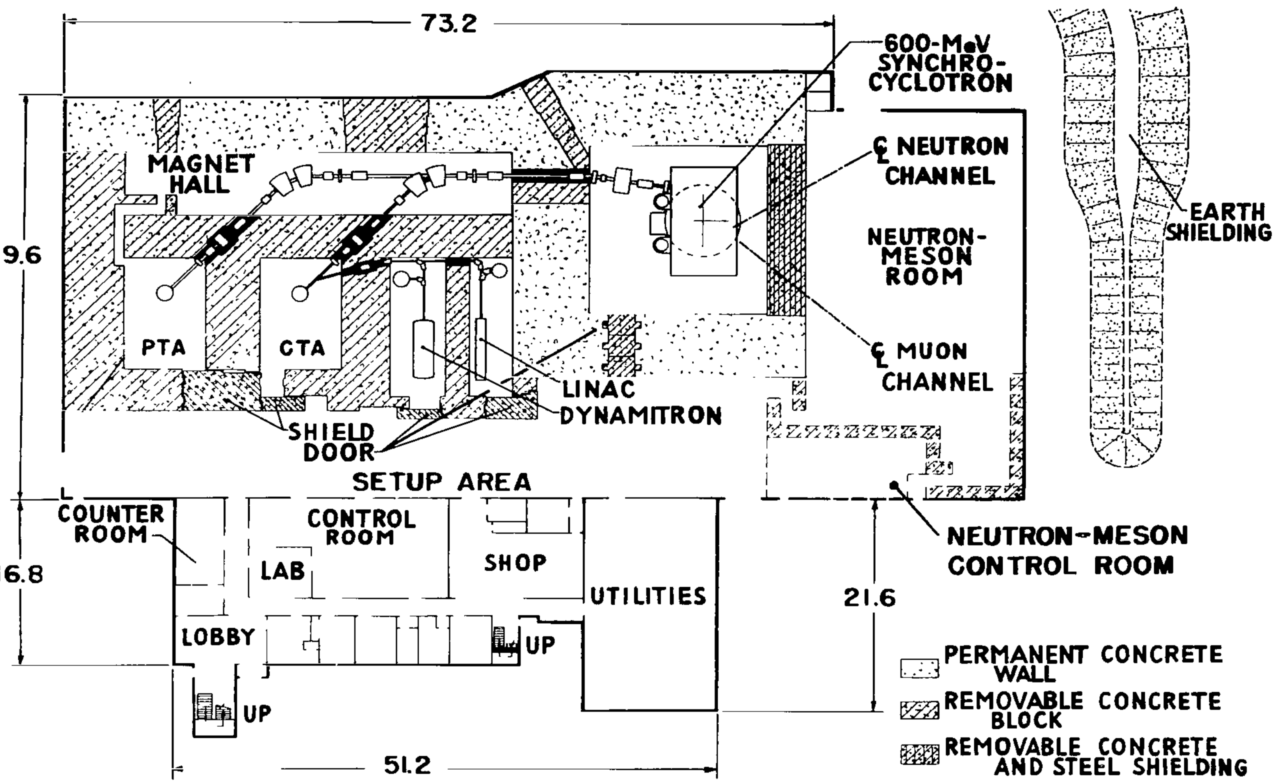


Figure 1.- Plan view of the NASA Space Radiation Effects Laboratory. All dimensions are in meters.

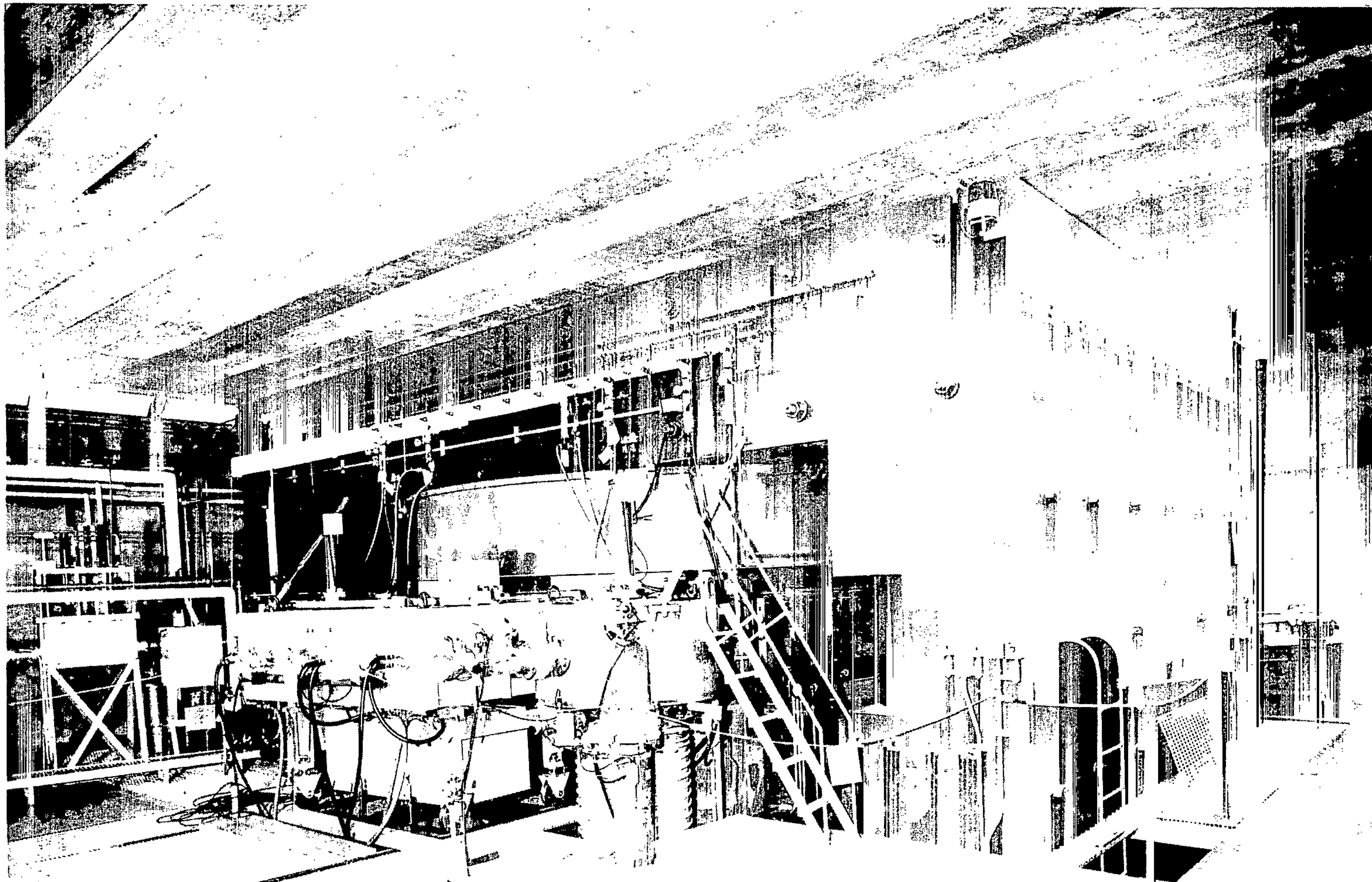


Figure 2.- The SREL 600-MeV proton synchrocyclotron. L-65-8622

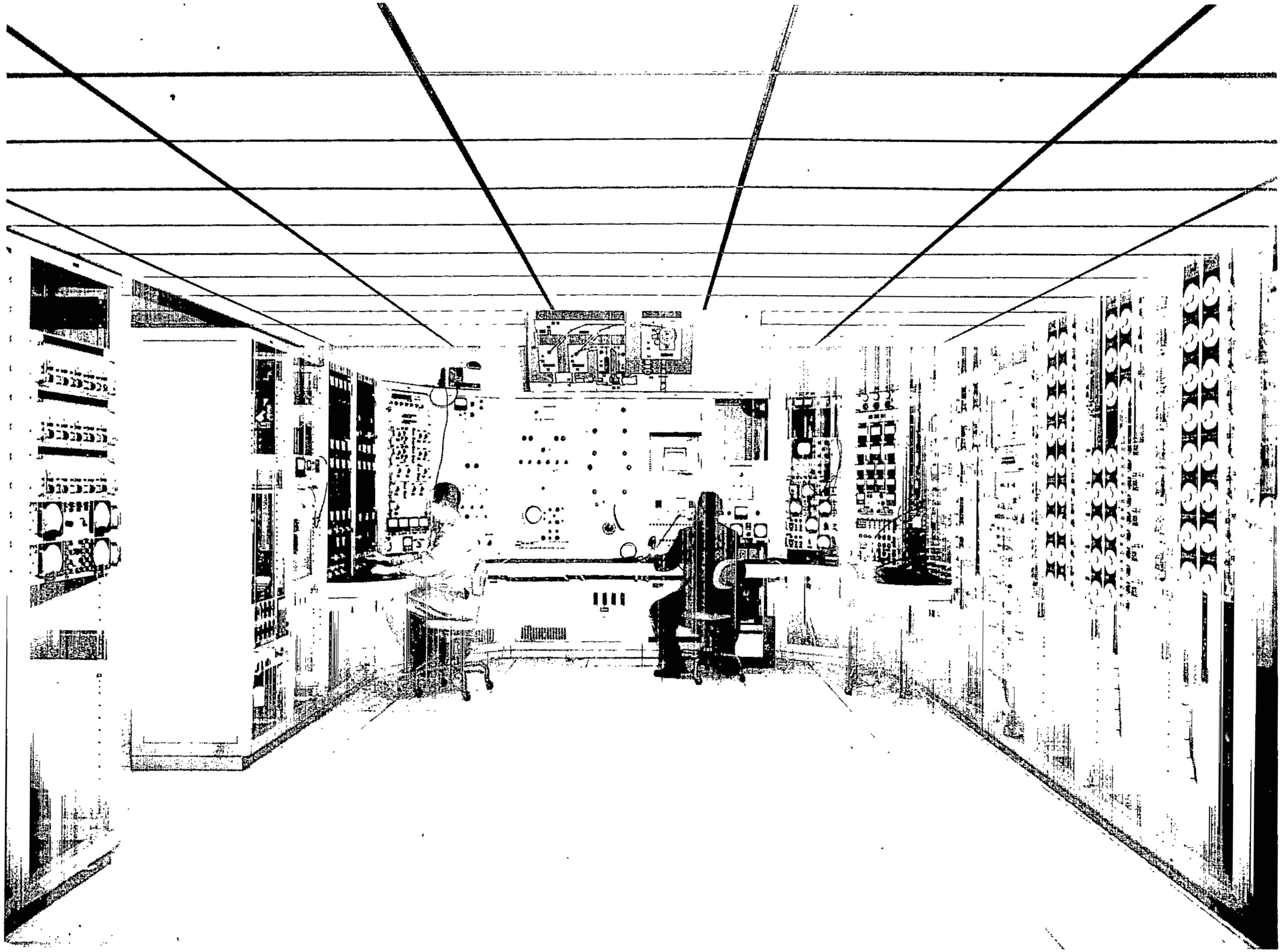


Figure 3.- Control panels for the 600-MeV proton synchrocyclotron. L-65-8616

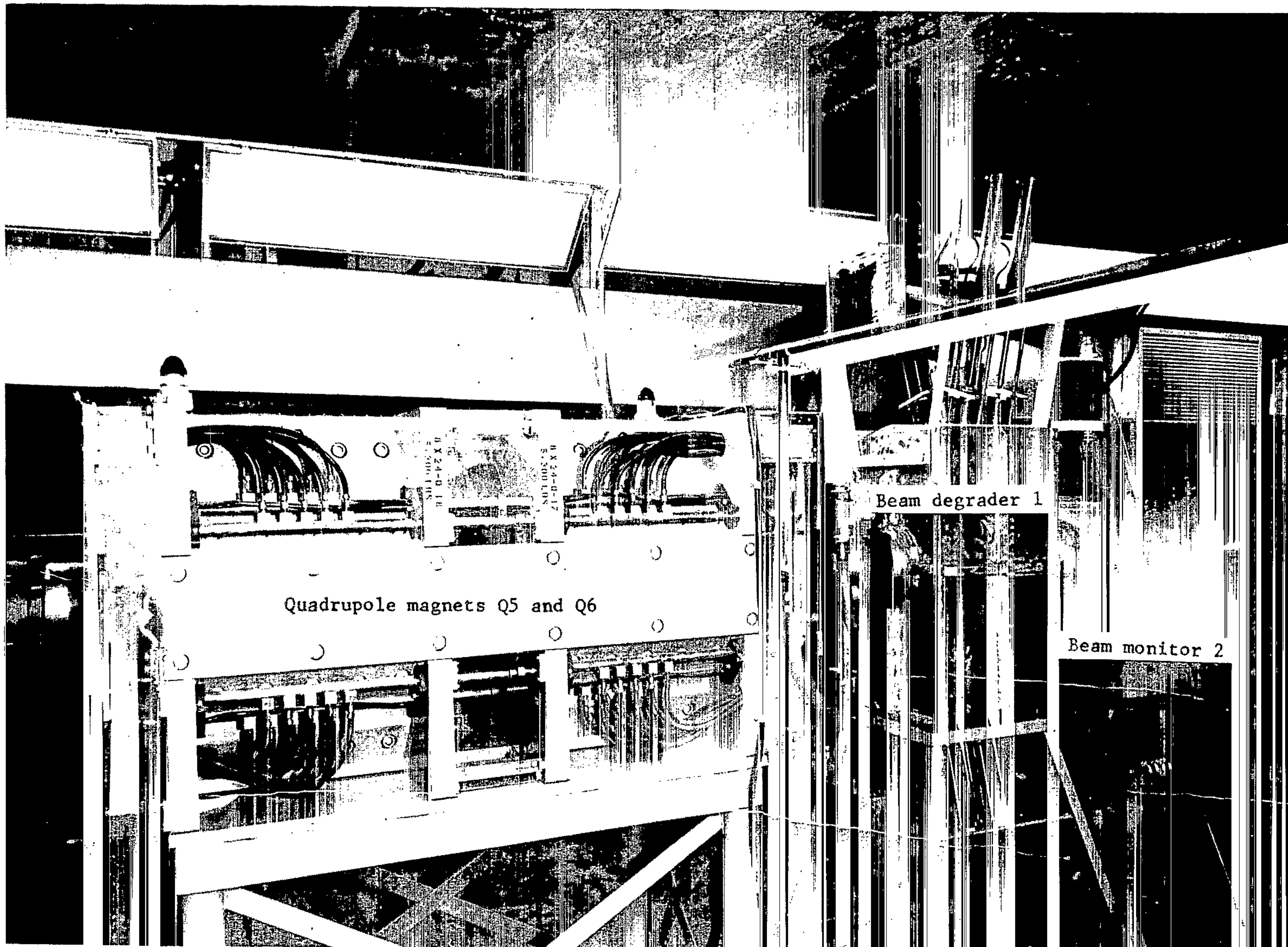


Figure 4.- A section of the proton beam transport system showing a quadrupole pair, beam degrader, and beam monitor. L-66-8547.1

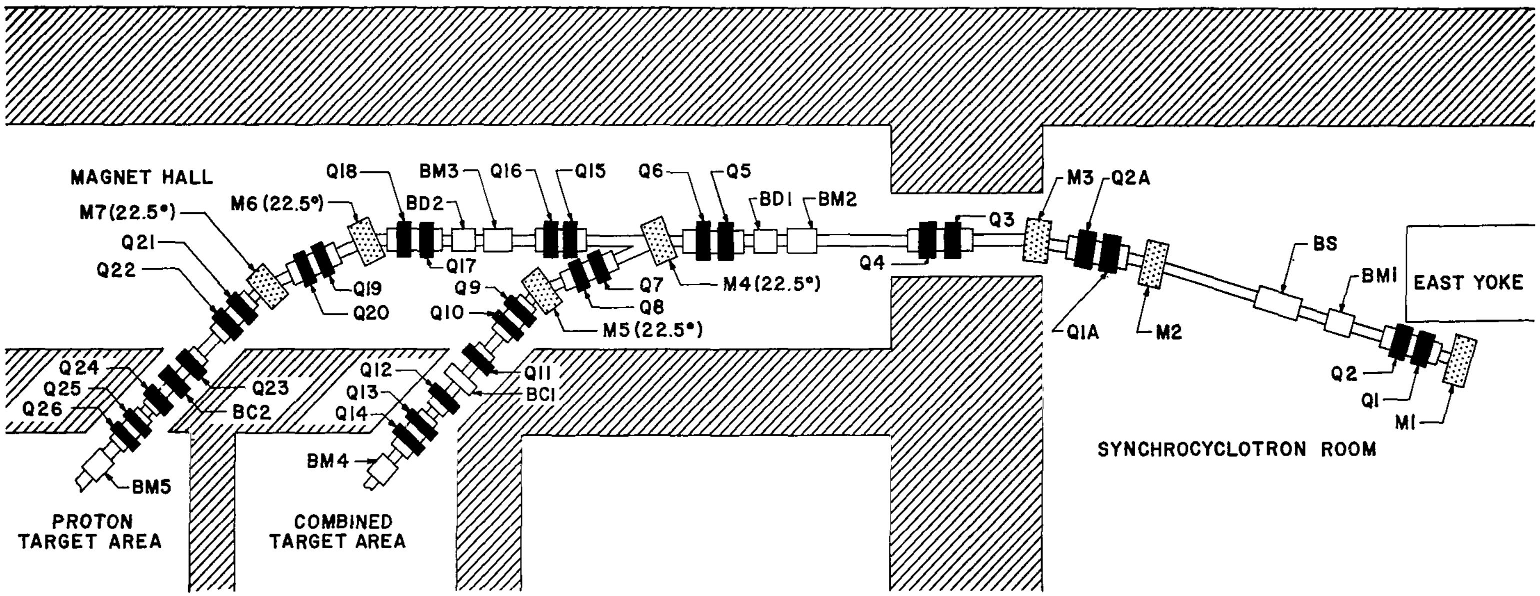


Figure 5.- Schematic diagram of the proton beam transport system at SREL.

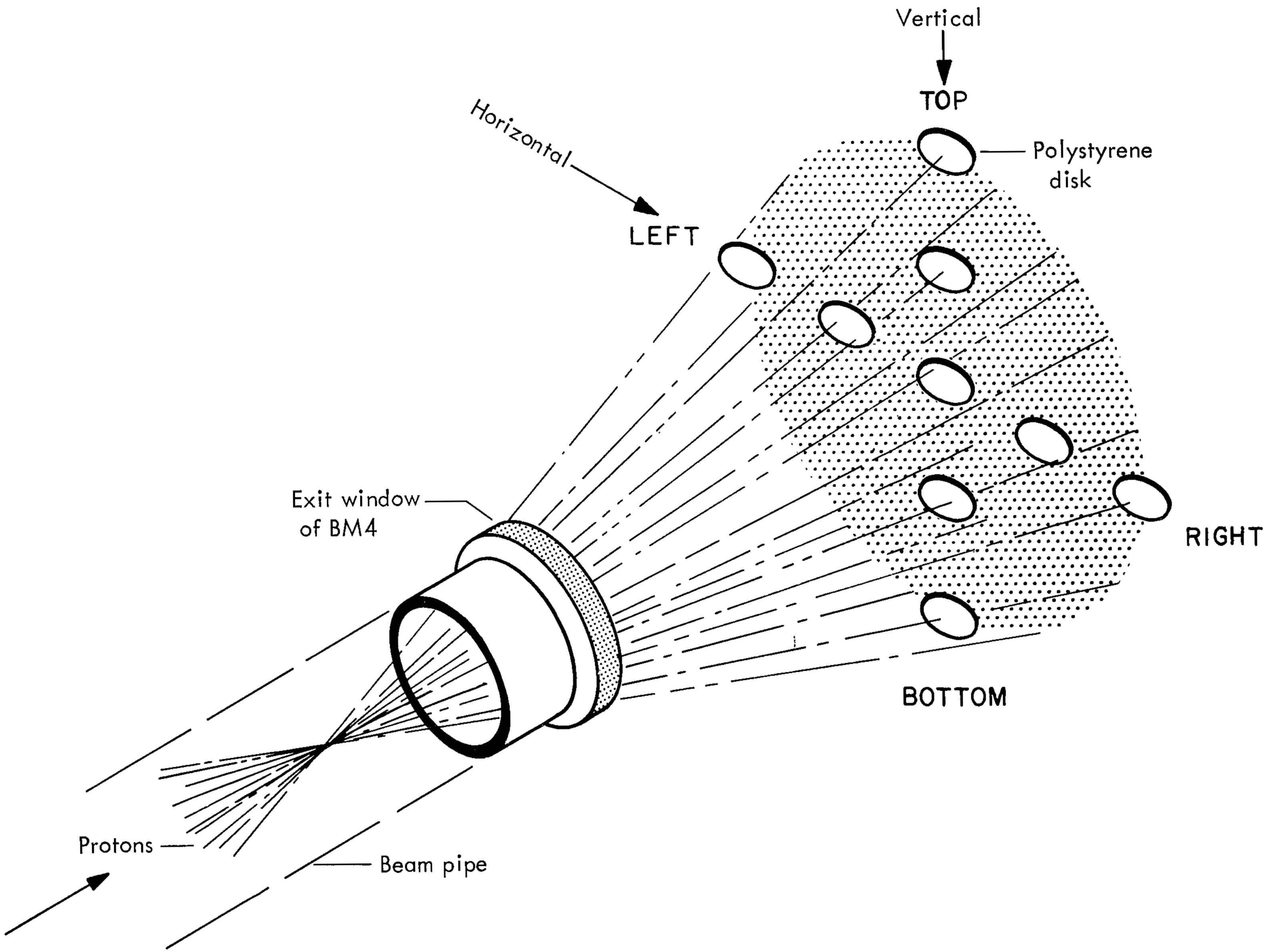


Figure 6.- Schematic diagram illustrating polystyrene disk array used in profile measurements.

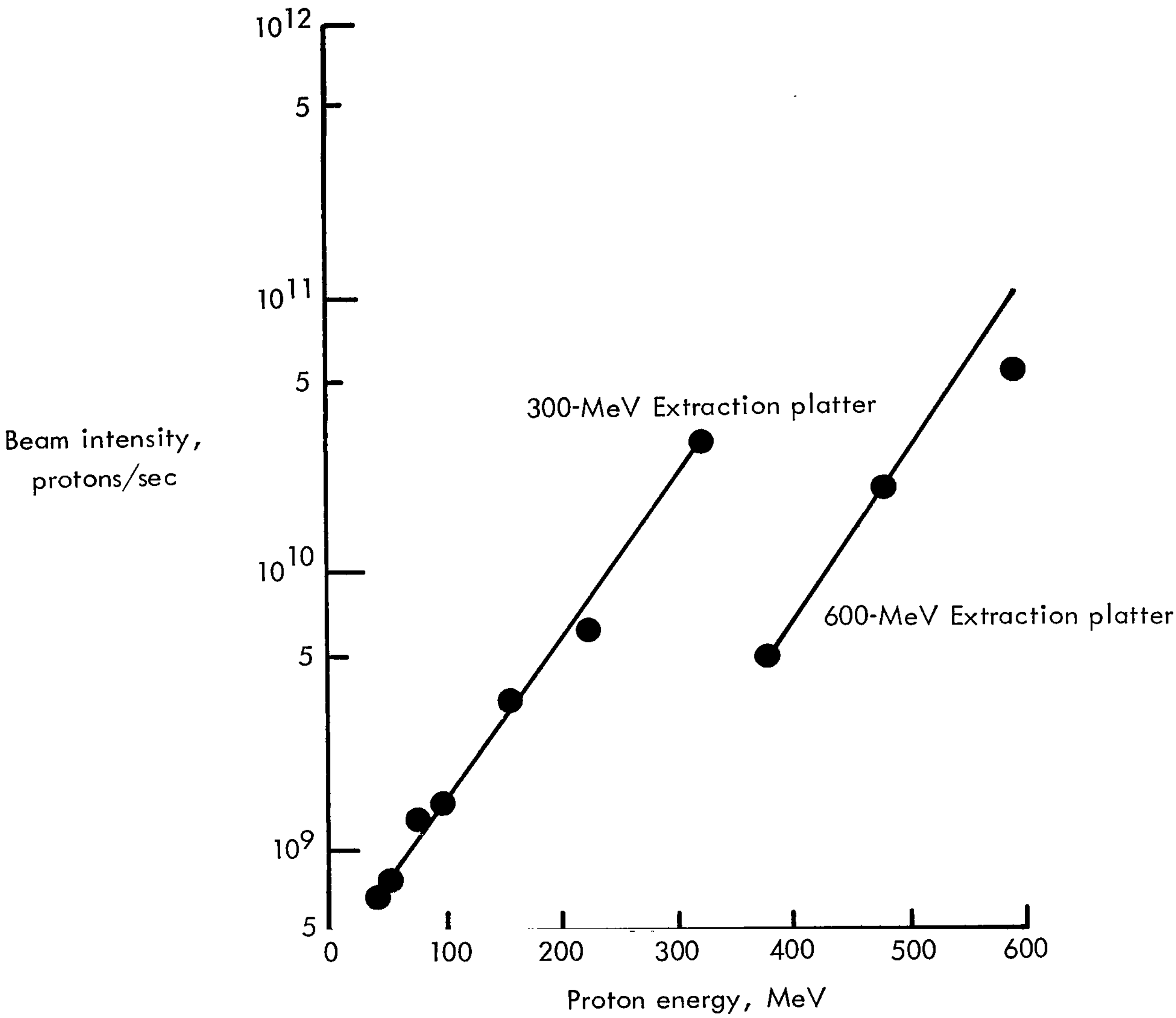


Figure 7.- Variation of proton beam intensity with proton energy. $C^{12}(p,pn)C^{11}$ reaction (ref. 1).

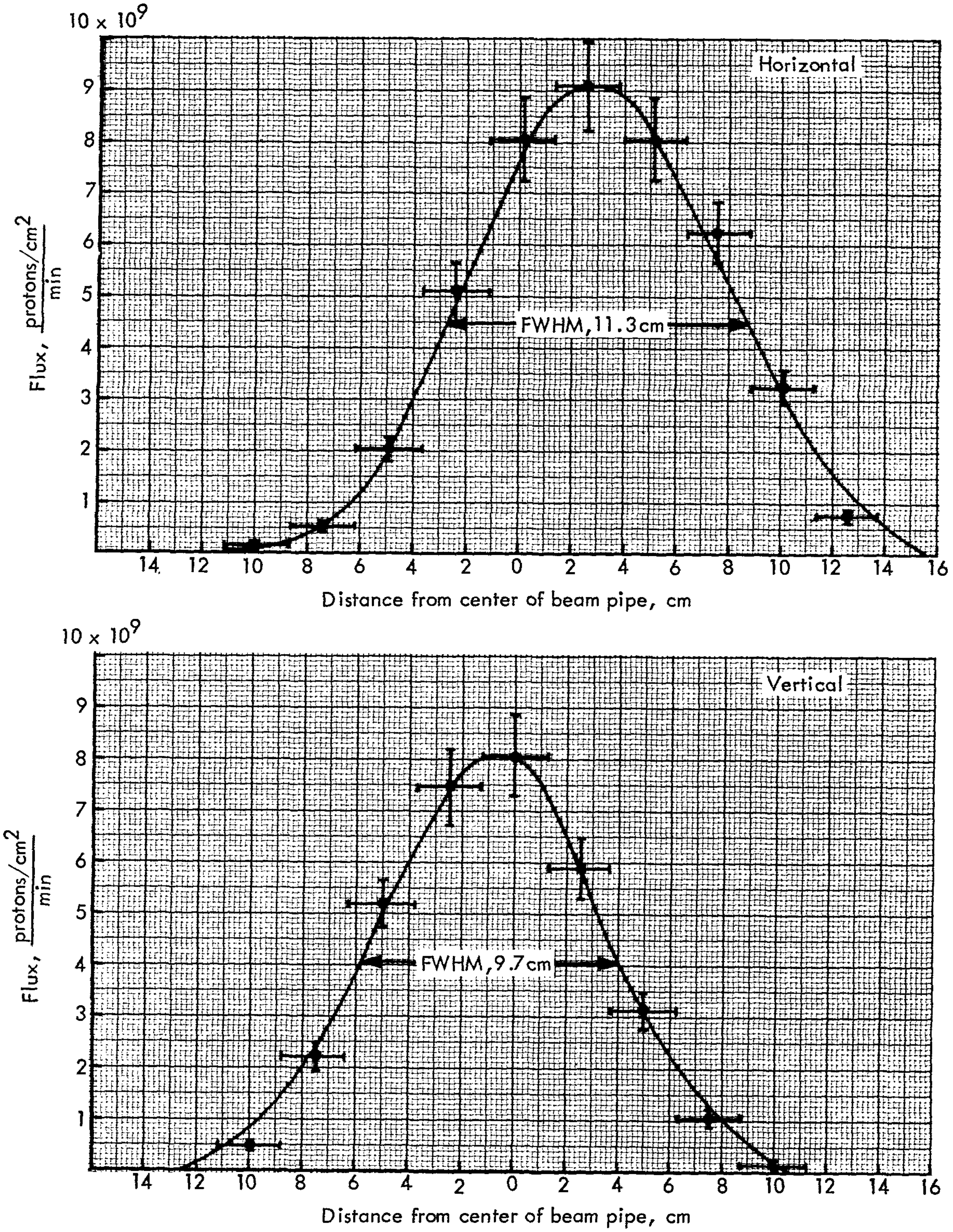


Figure 8.- Horizontal and vertical profiles of a 225-MeV large-area proton beam at 3.05 meters from BM4 exit window.

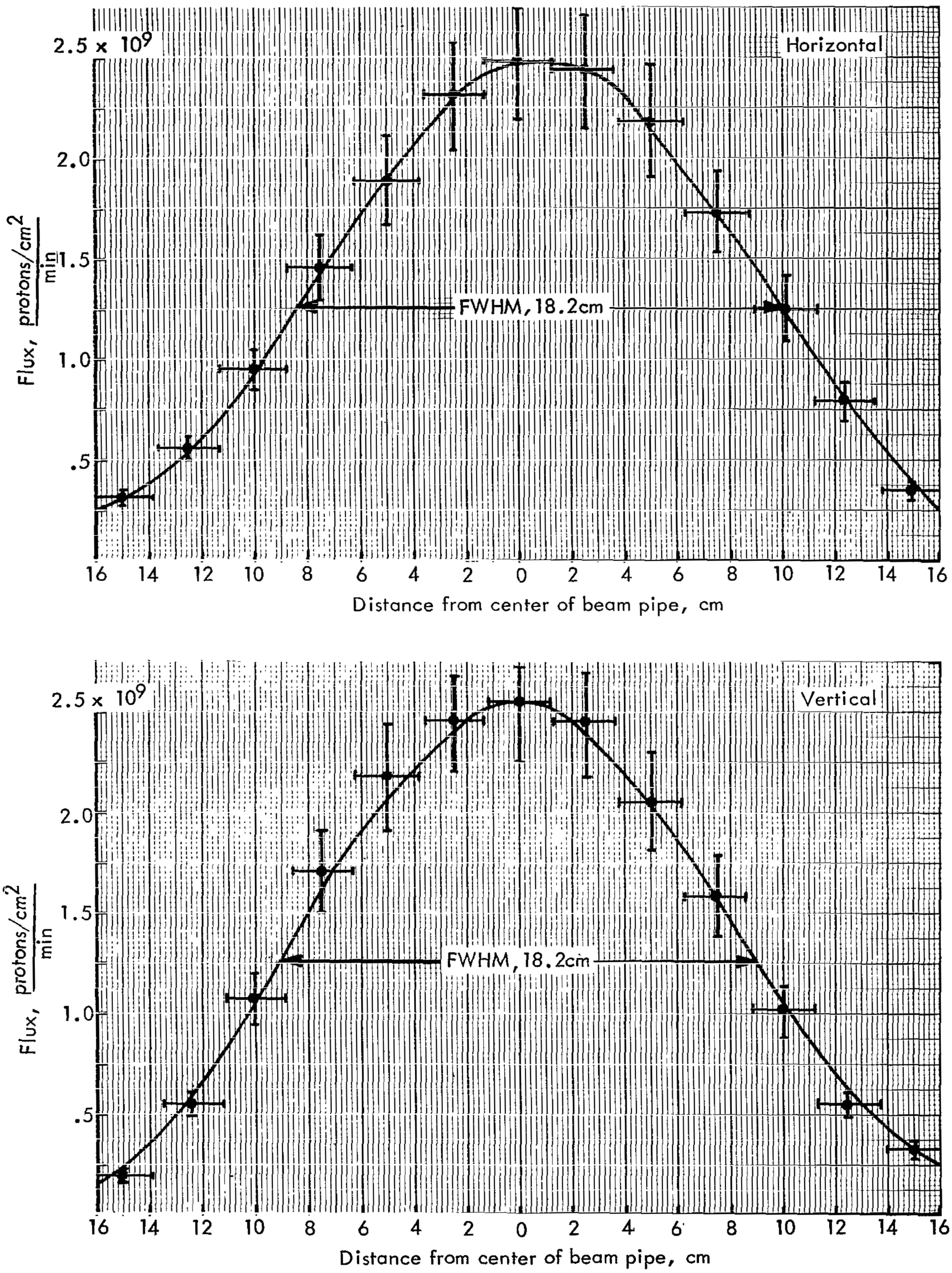


Figure 9.- Horizontal and vertical profiles of a 225-MeV large-area proton beam at 7.62 meters from BM4 exit window.

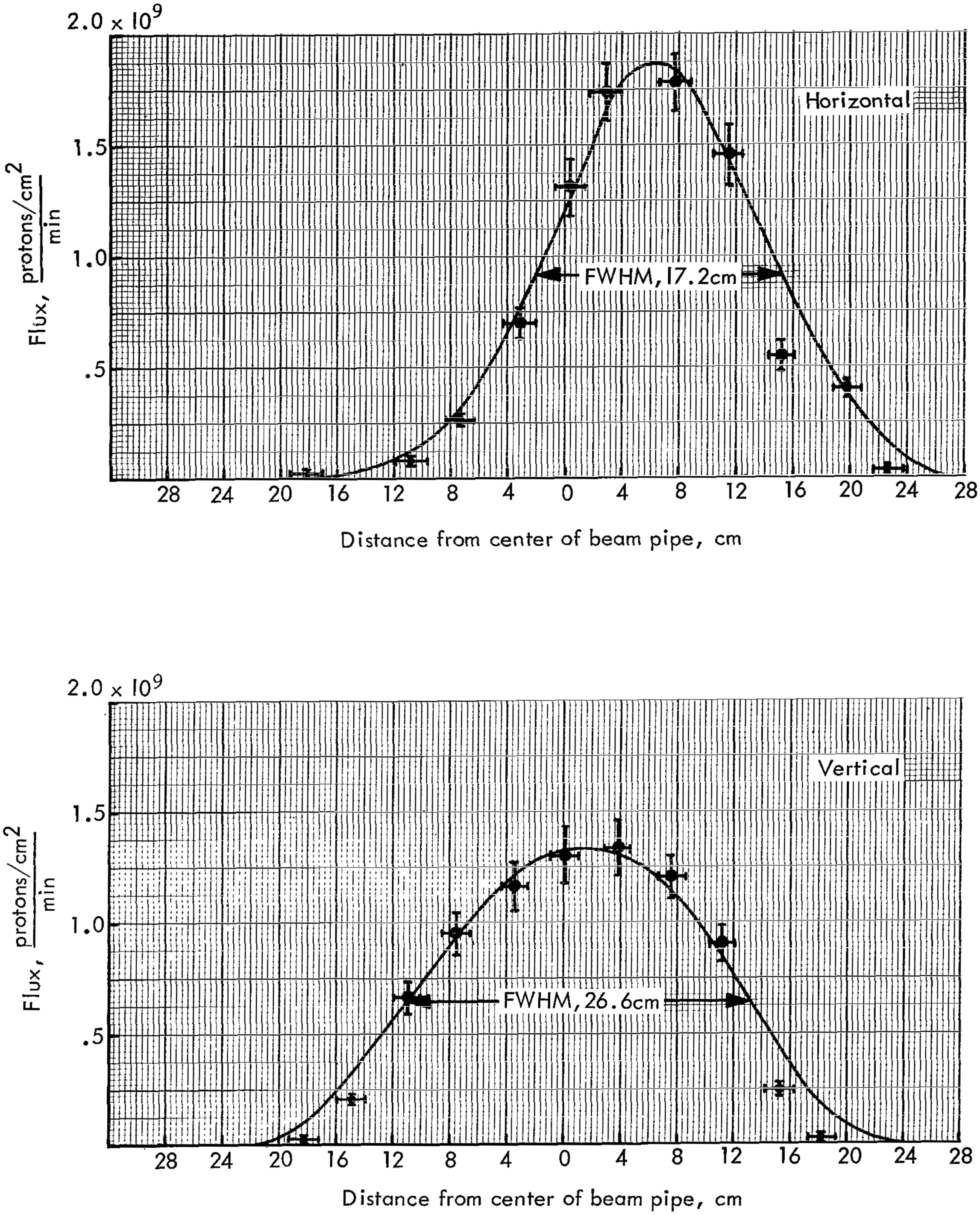
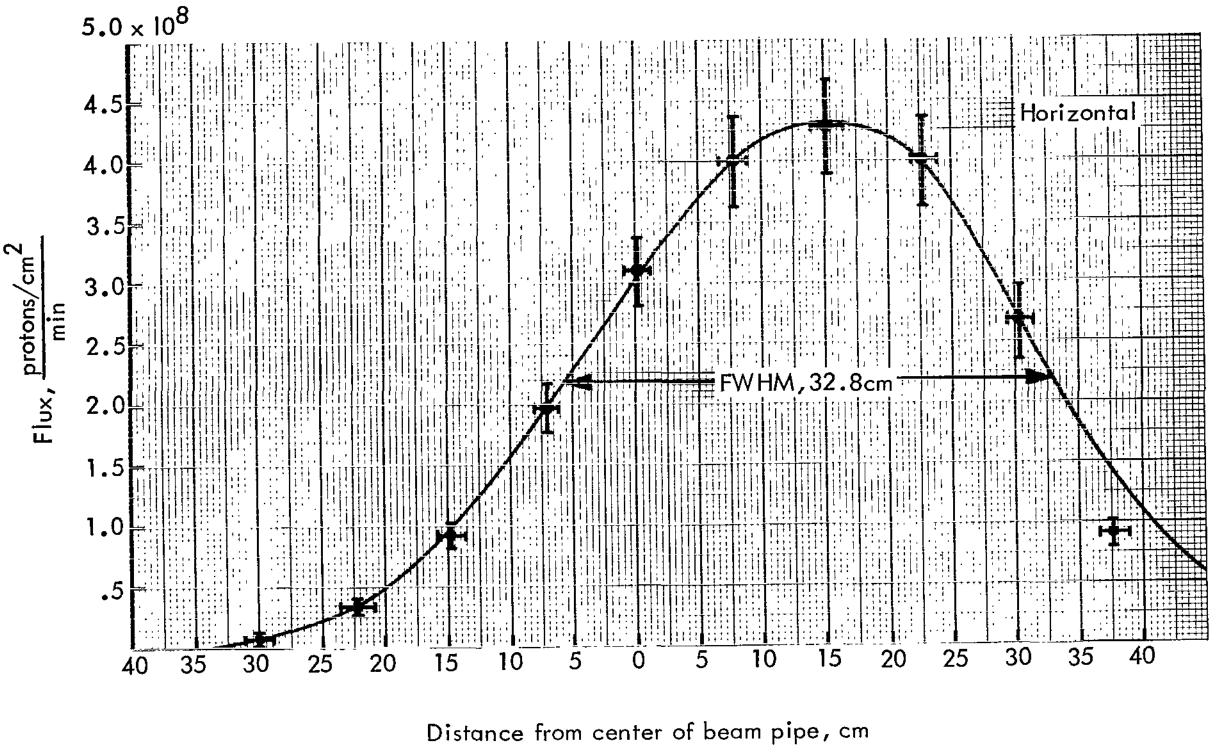


Figure 10.- Horizontal and vertical profiles of a 155-MeV large-area proton beam at 3.05 meters from BM4 exit window.



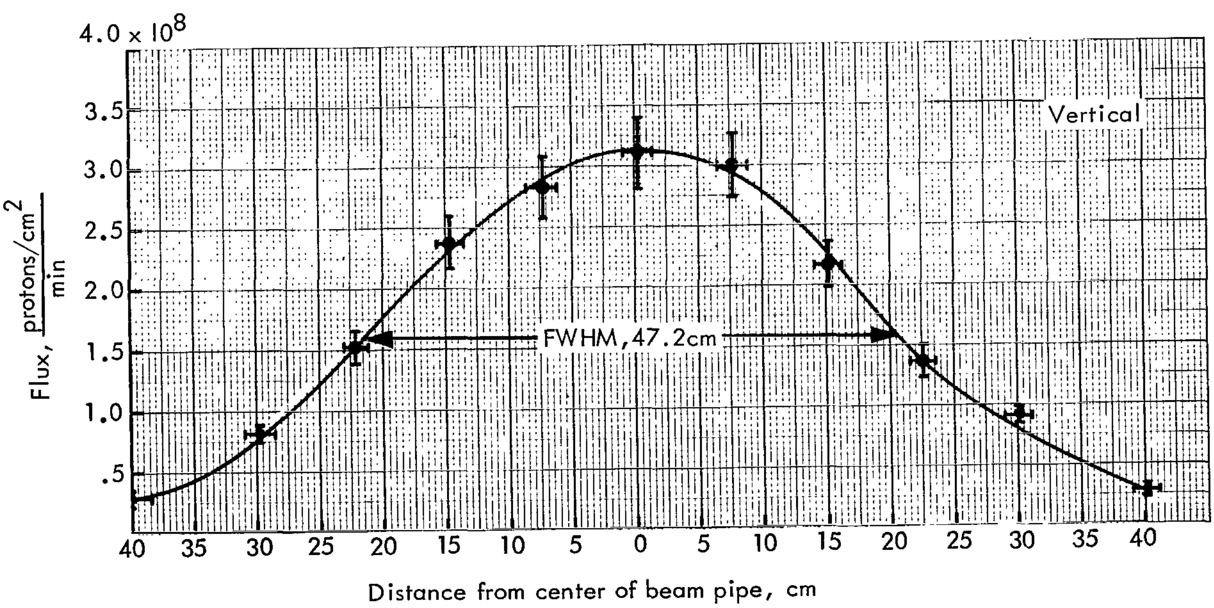


Figure 11.- Horizontal and vertical profiles of a 155-MeV large-area proton beam at 7.62 meters from BM4 exit window.

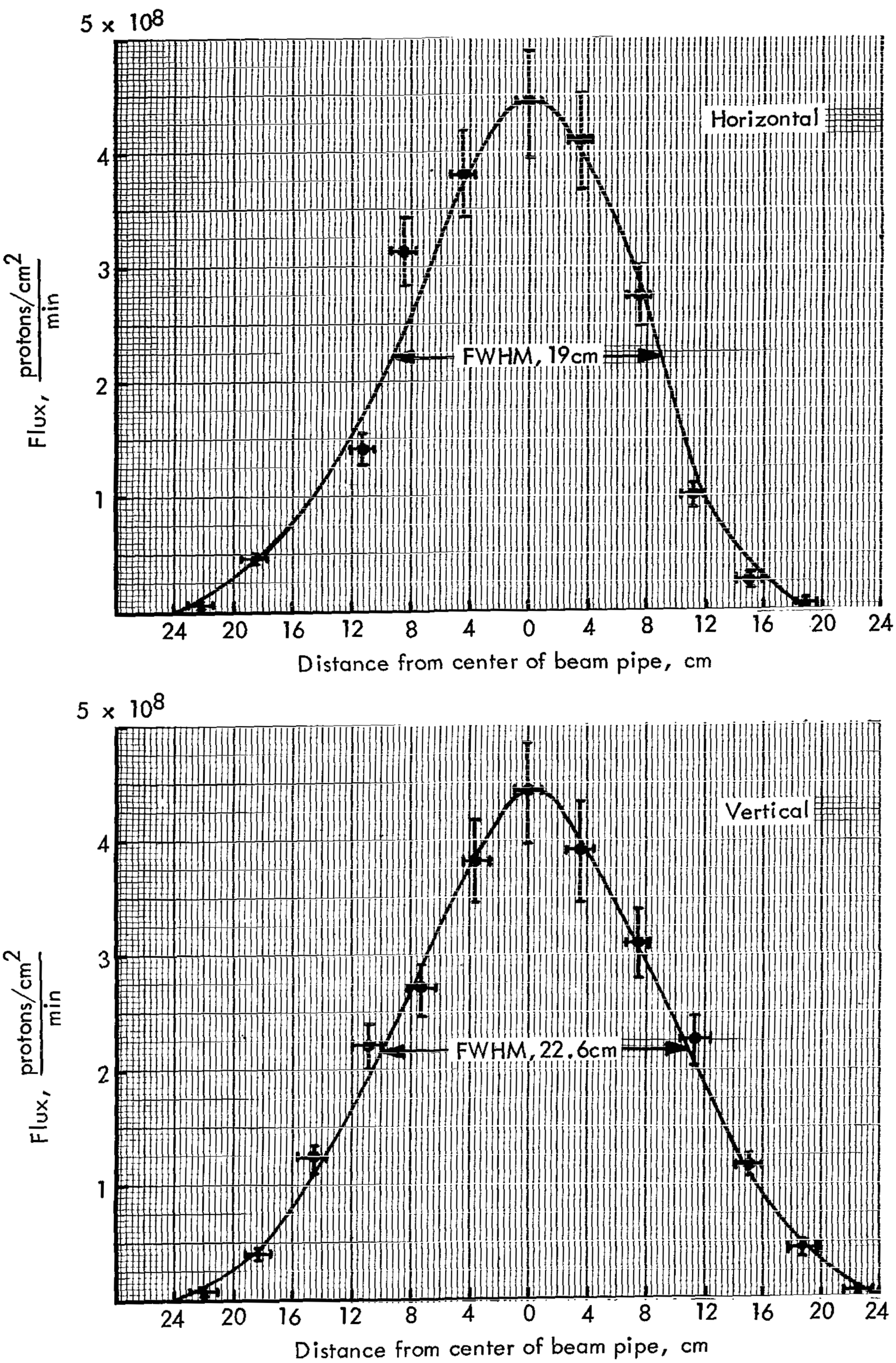
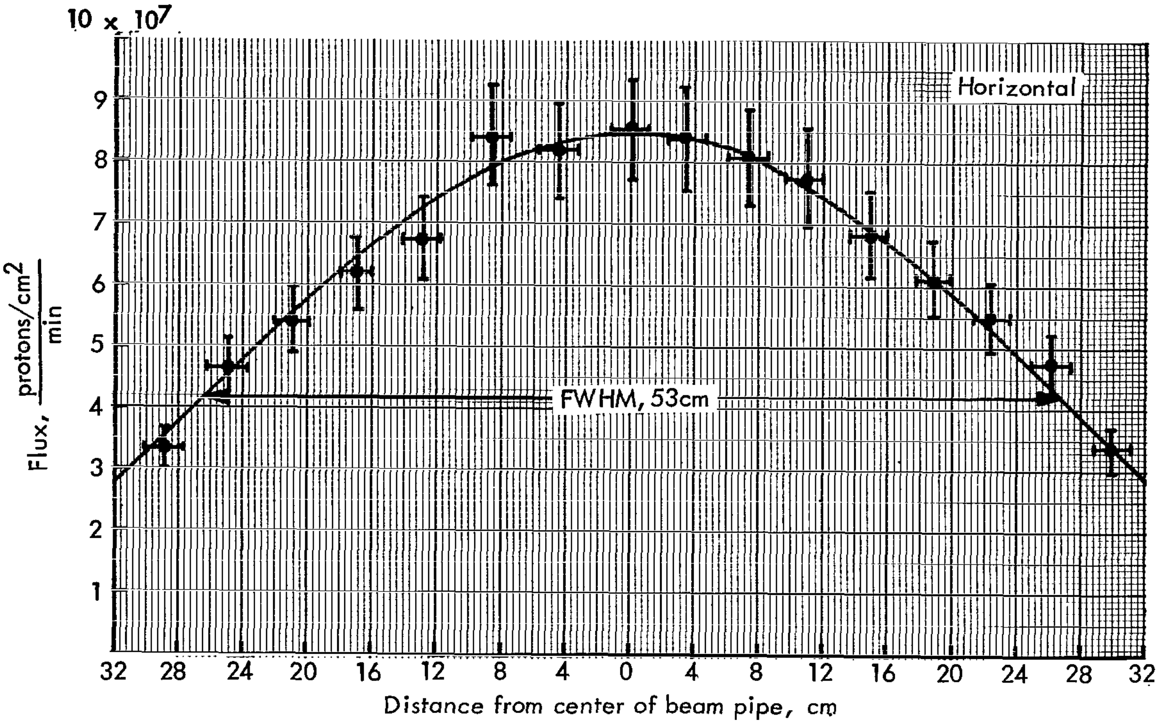


Figure 12.- Horizontal and vertical profiles of a 95-MeV large-area proton beam at 3.05 meters from BM4 exit window.



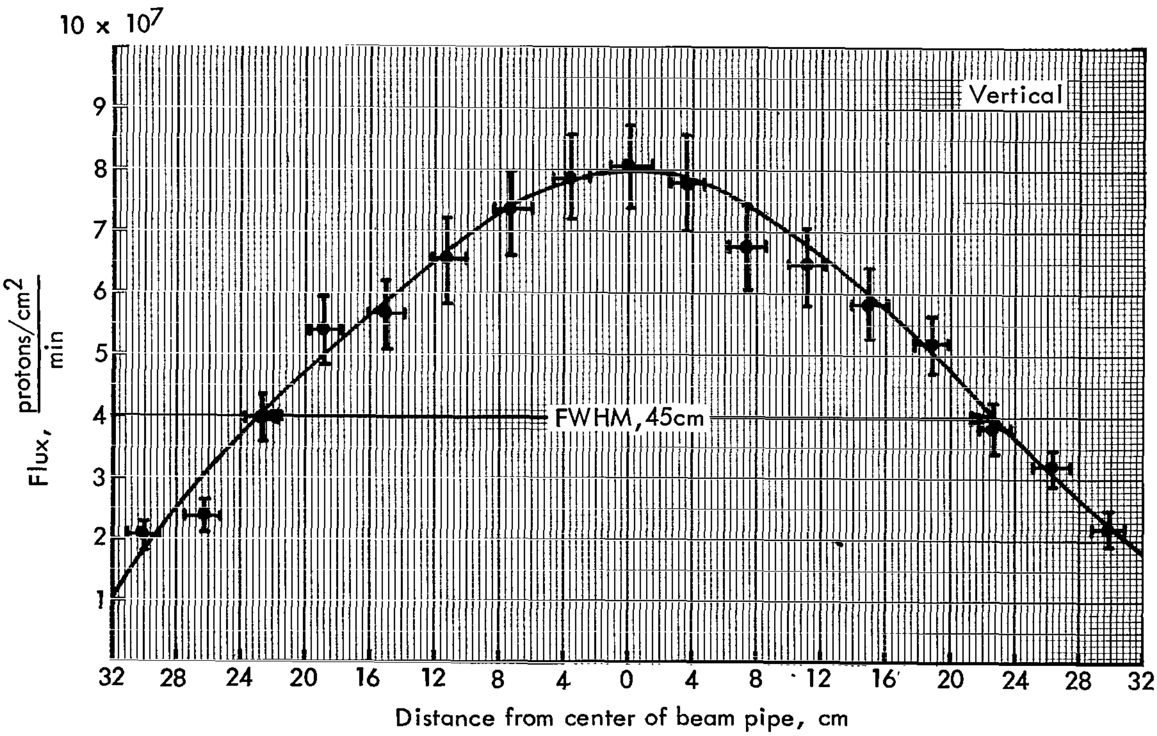


Figure 13.- Horizontal and vertical profiles of a 95-MeV large-area proton beam at 7.62 meters from BM4 exit window.

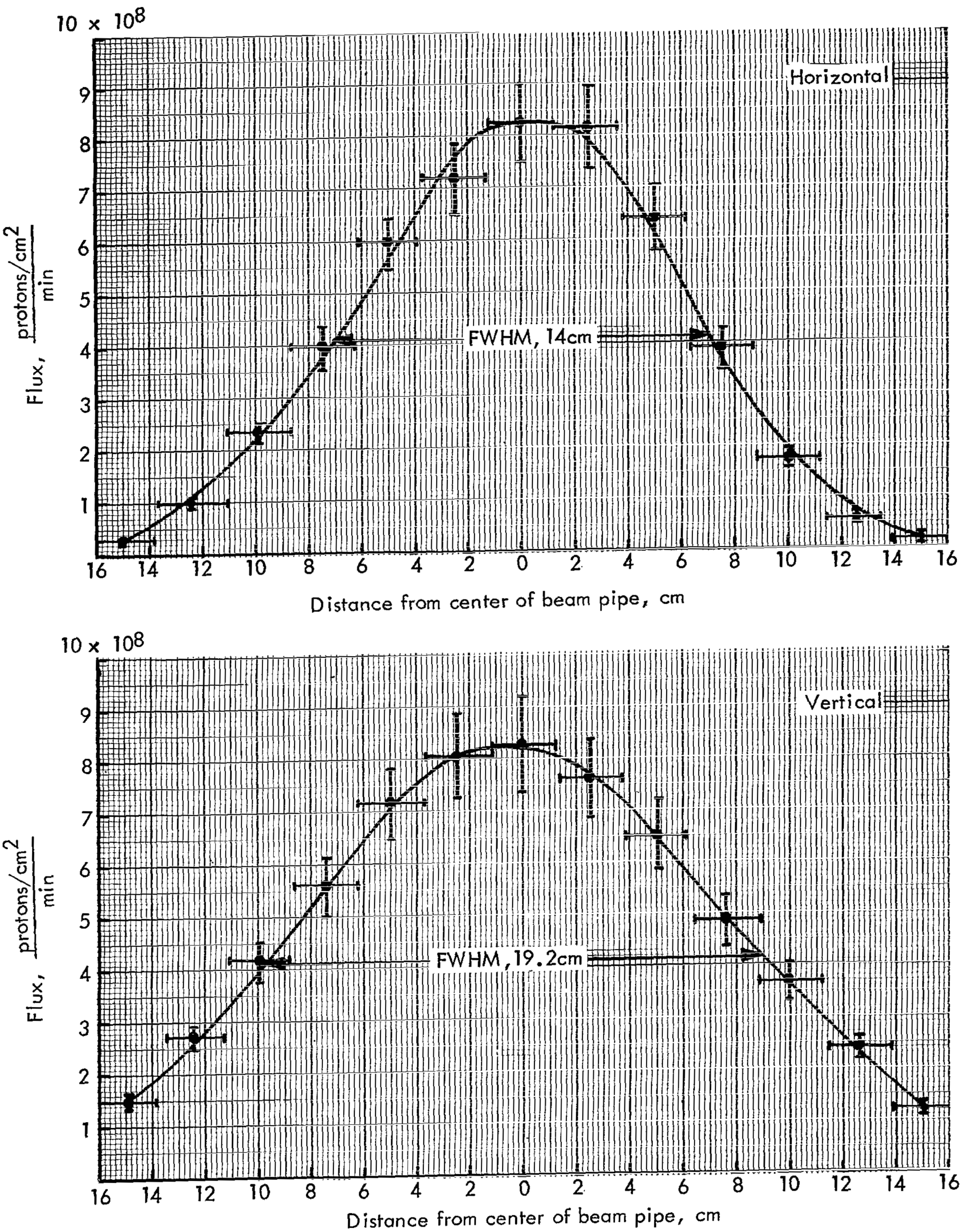
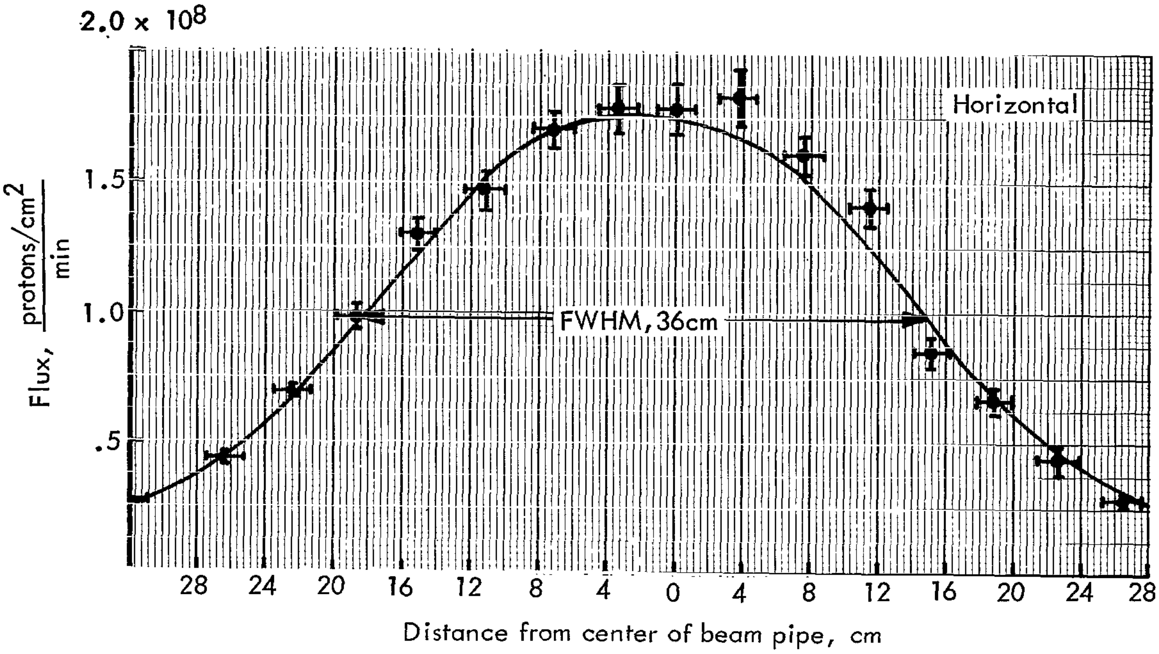


Figure 14.- Horizontal and vertical profiles of a 75-MeV large-area proton beam at 3.05 meters from BM4 exit window.



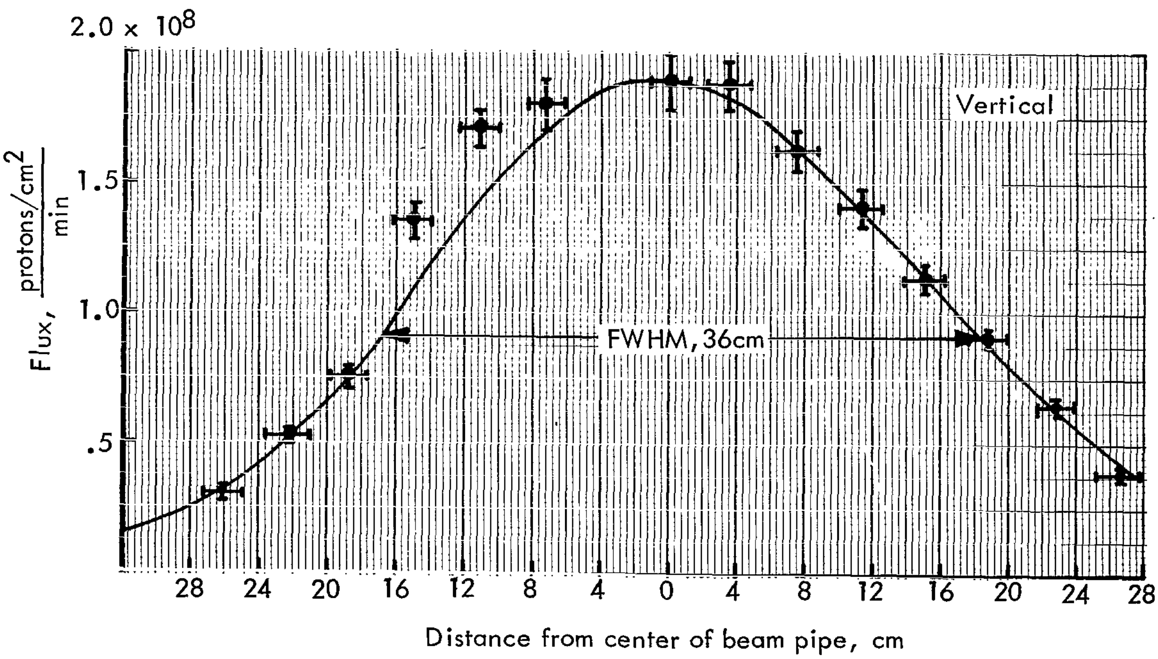
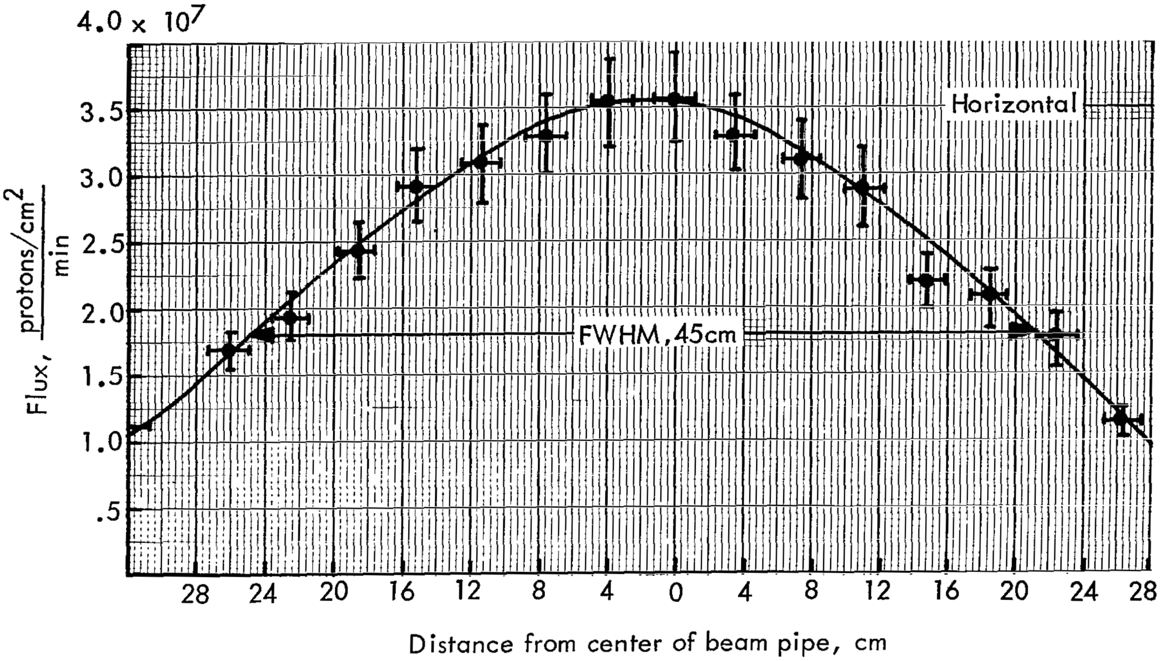


Figure 15.- Horizontal and vertical profiles of a 75-MeV large-area proton beam at 7.62 meters from BM4 exit window.



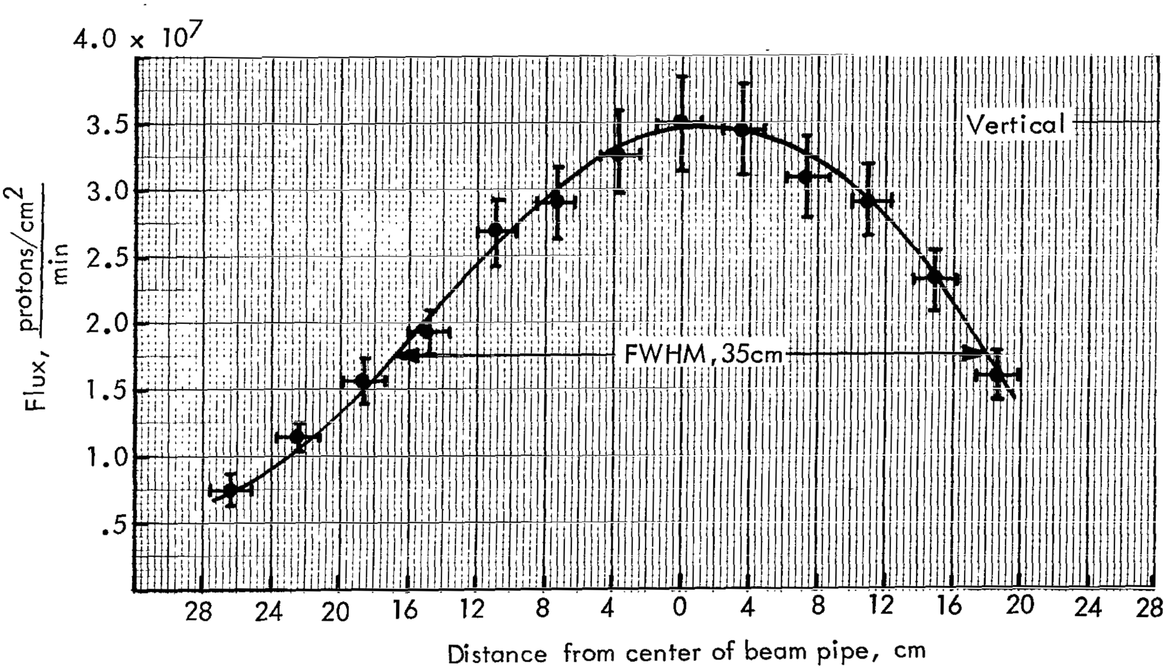
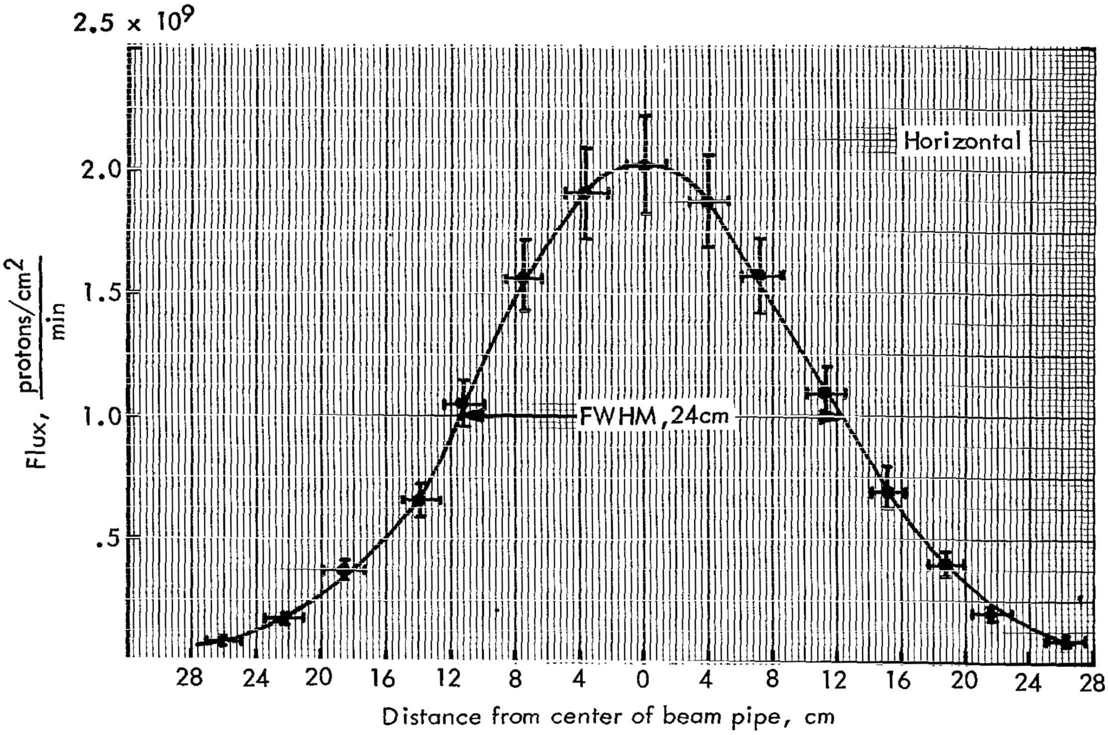


Figure 16.- Horizontal and vertical profiles of a 50-MeV large-area proton beam at 3.05 meters from BM4 exit window.



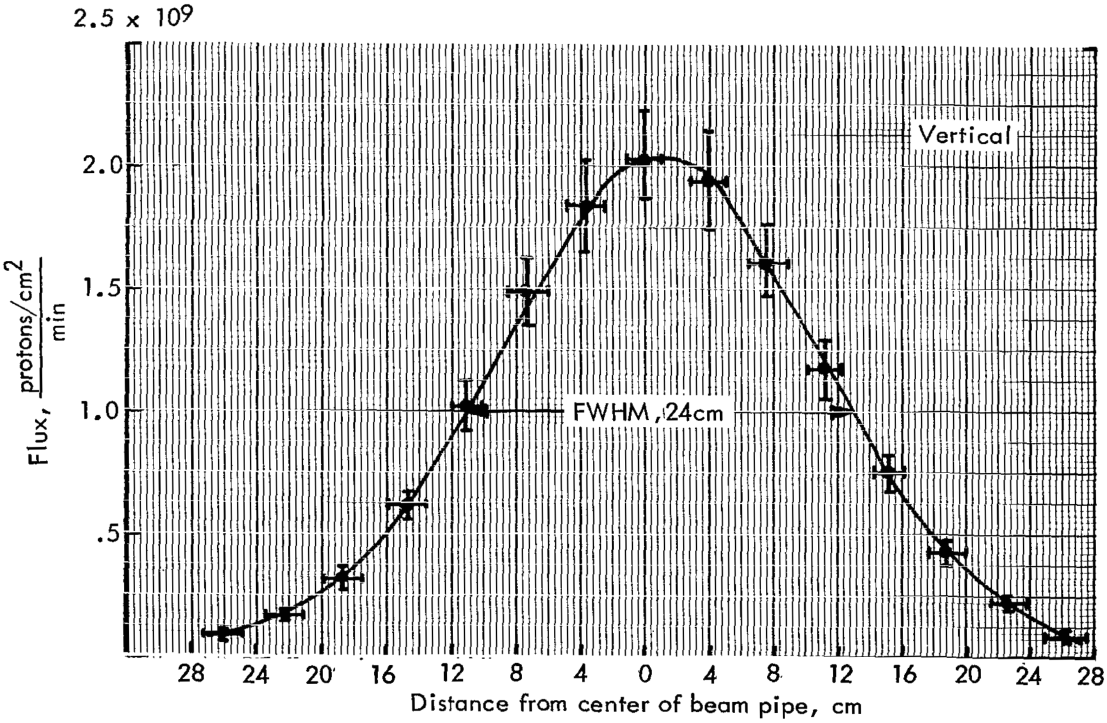


Figure 17.- Horizontal and vertical profiles of a 194-MeV Coulomb scattered large-area proton beam.

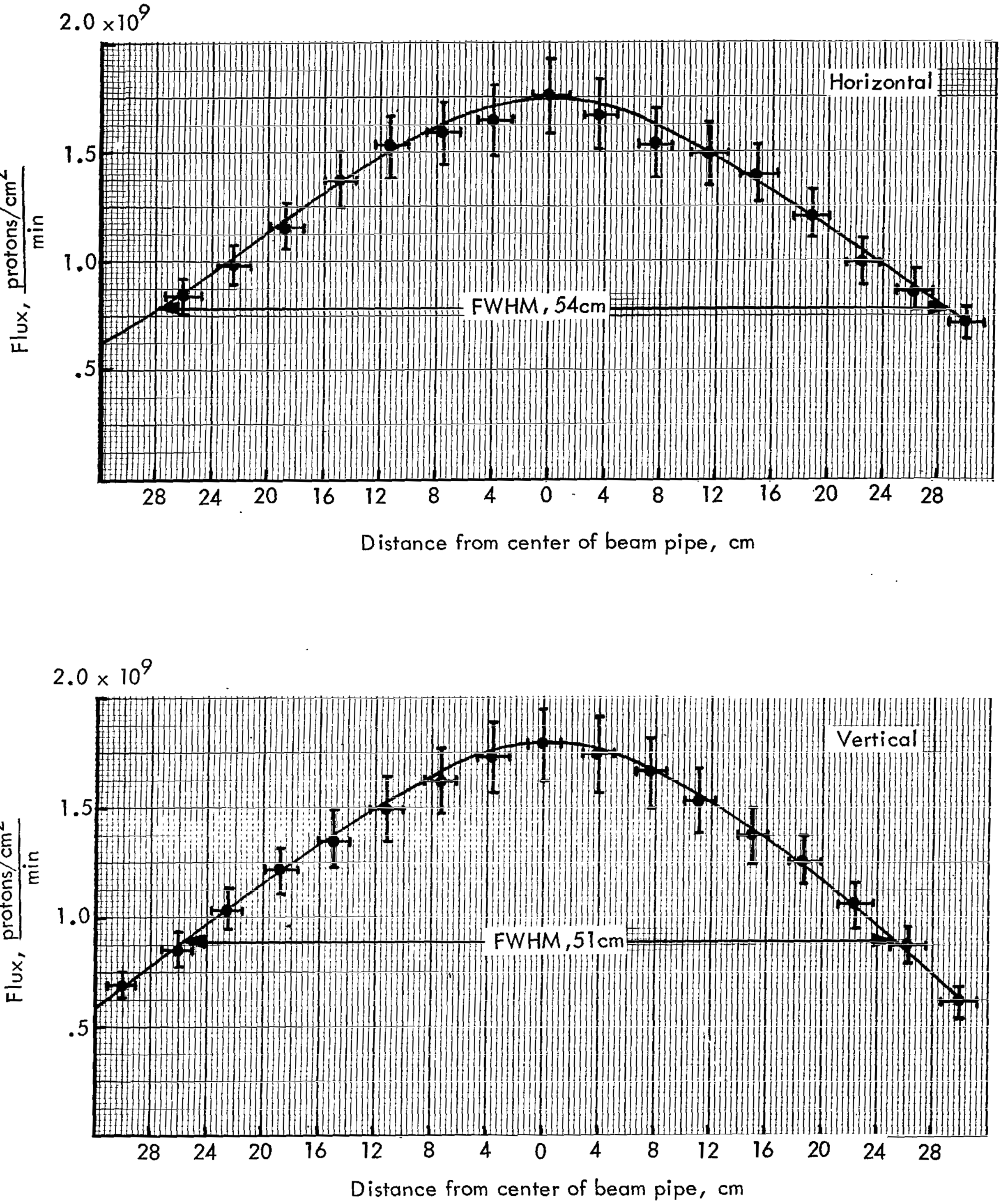


Figure 18.- Horizontal and vertical profiles of a 146-MeV Coulomb scattered large-area proton beam.

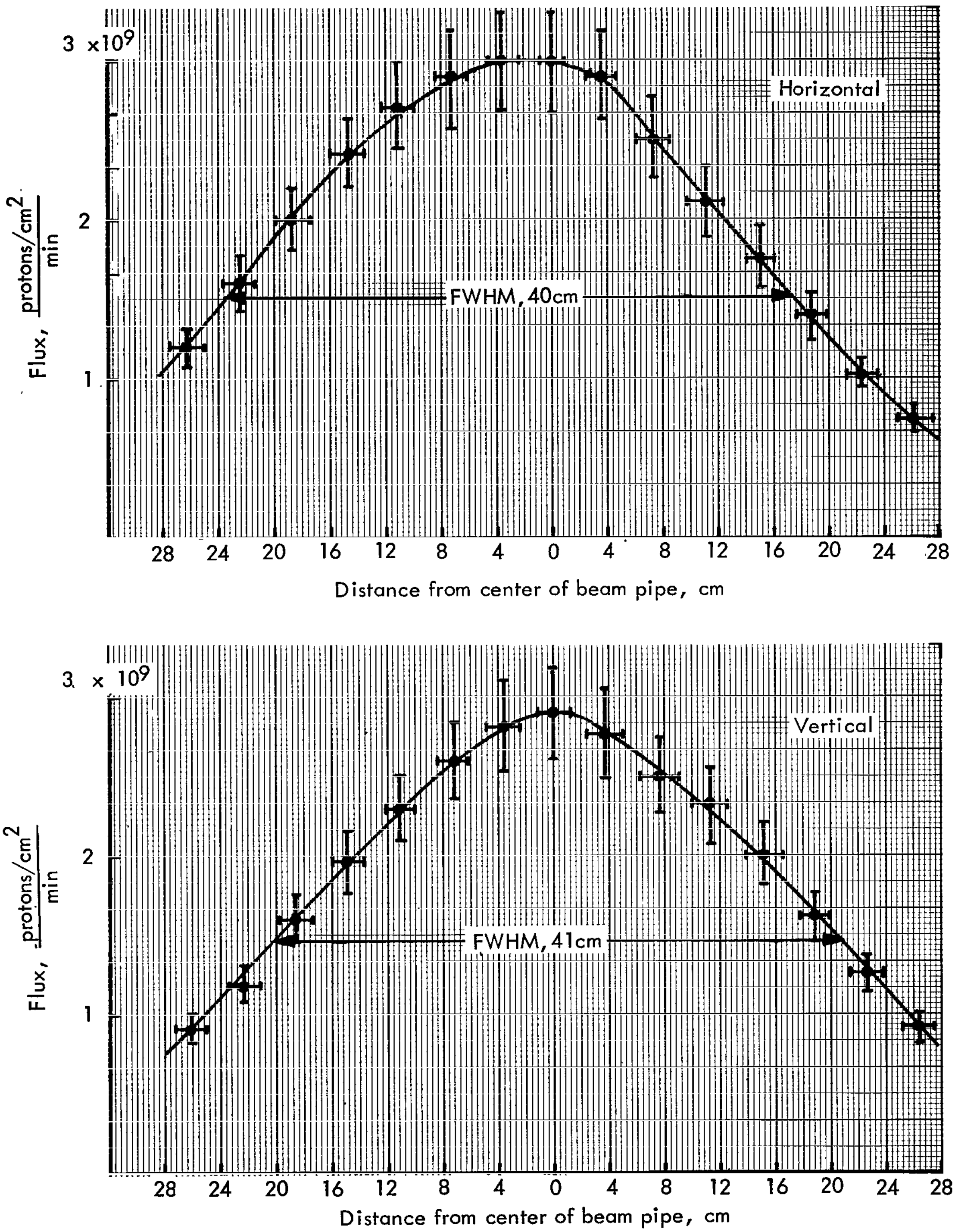
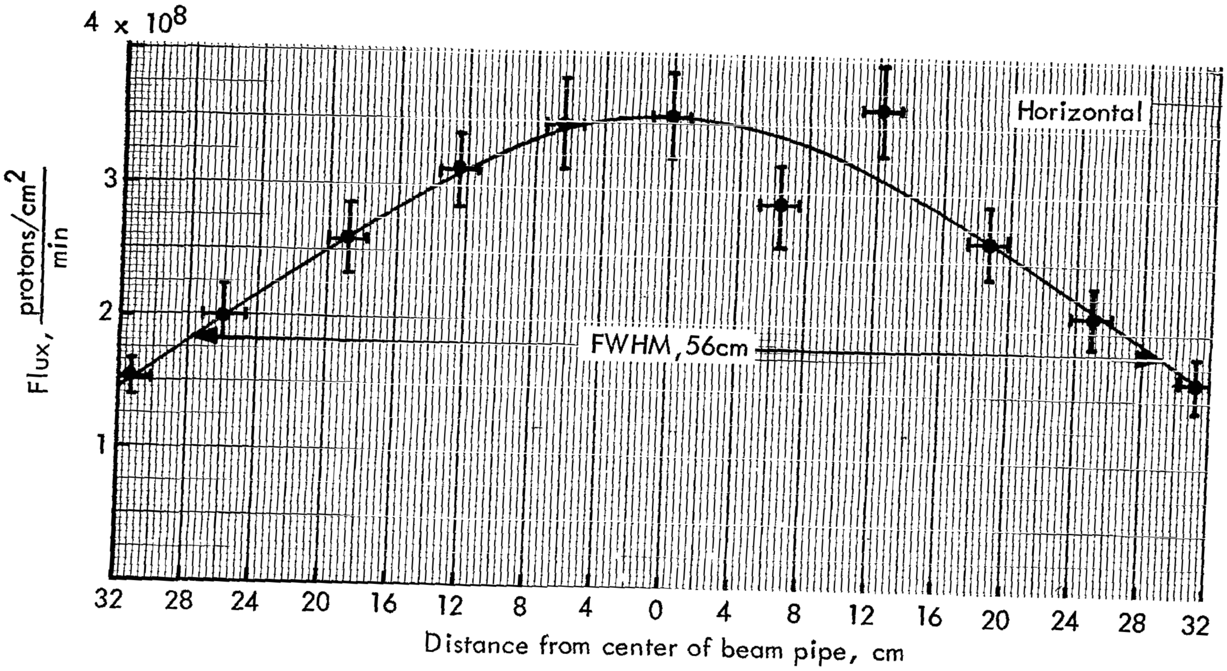


Figure 19.- Horizontal and vertical profiles of a 142-MeV Coulomb scattered large-area proton beam.



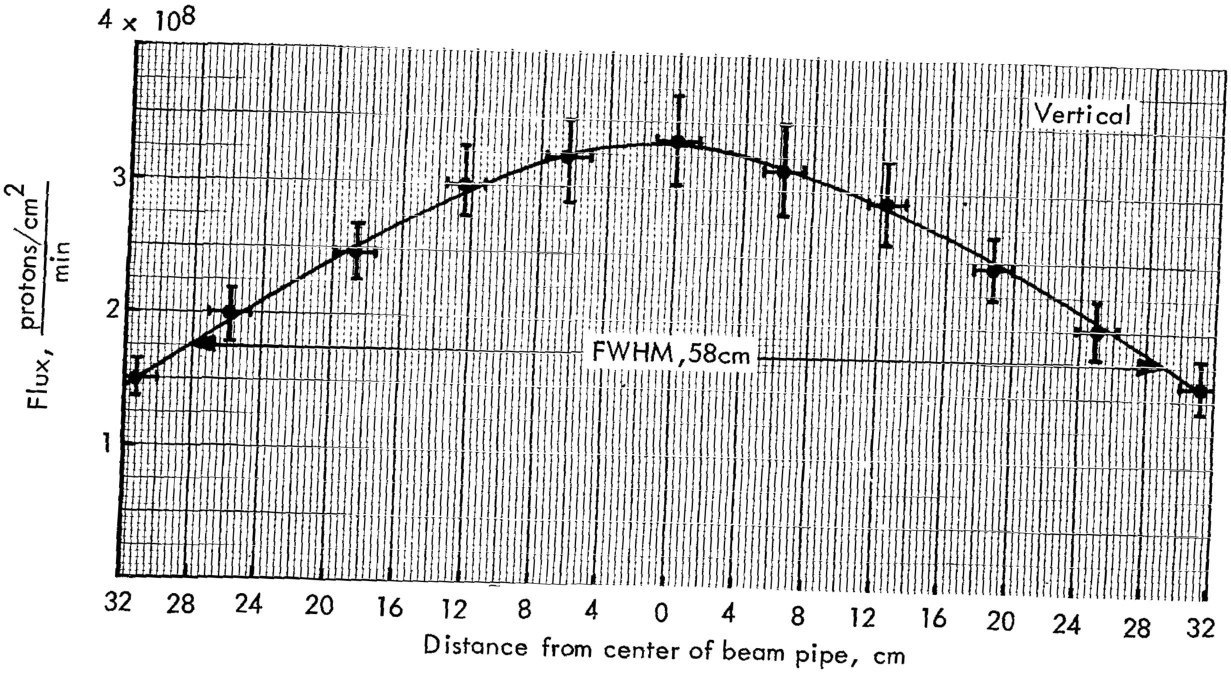
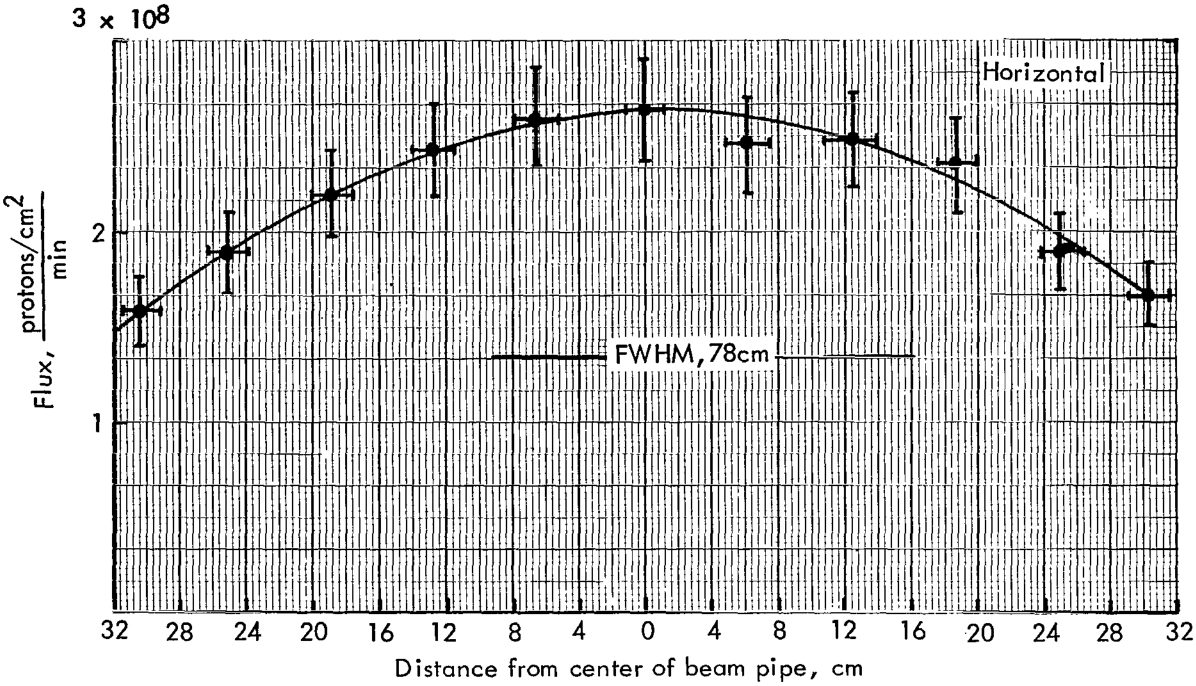


Figure 20.- Horizontal and vertical profiles of a 90-MeV Coulomb scattered large-area proton beam.



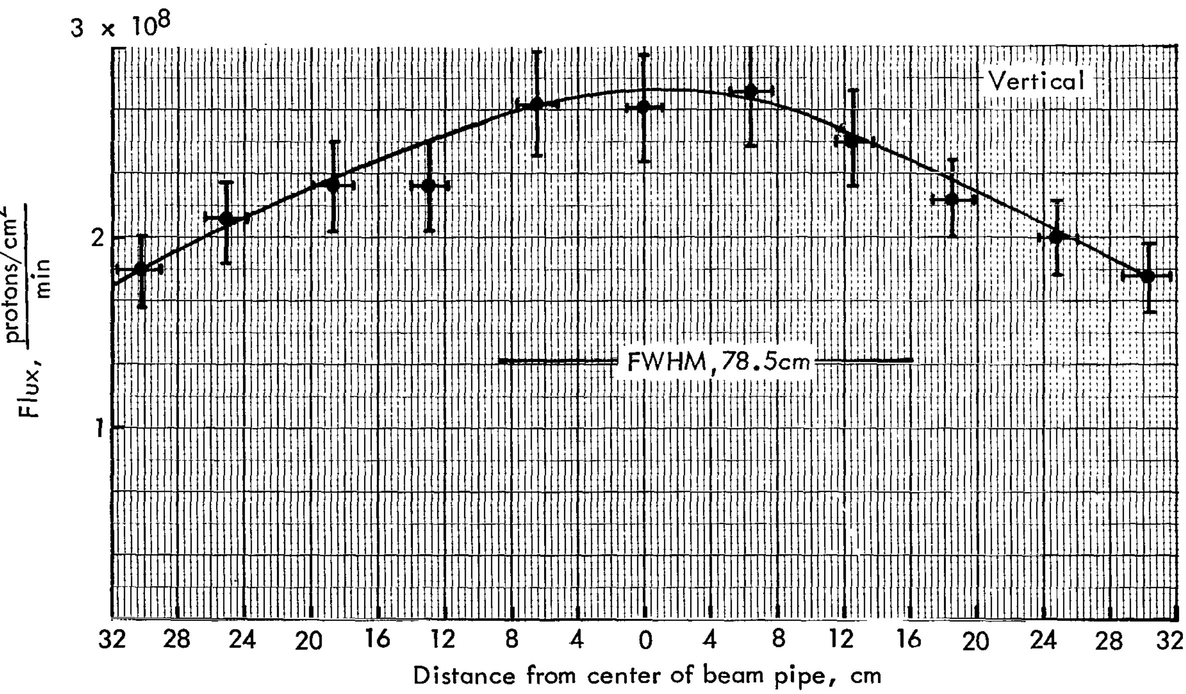


Figure 21.- Horizontal and vertical profiles of a 31-MeV Coulomb scattered large-area proton beam.

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